ACCURACY ASSESSMENT OF LOW-COST TERRESTRIAL AND UAV-BASED PHOTOGRAMMETRY FOR GEOMATICS APPLICATIONS IN ARCHITECTURAL AND CULTURAL HERITAGE CONTEXTS

Dissertation

submitted to and approved by the

Department of Architecture, Civil Engineering and Environmental Sciences
University of Braunschweig – Institute of Technology

and the

Department of Civil and Environmental Engineering
University of Florence

in candidacy for the degree of a

Doktor-Ingenieurin (Dr.-Ing.) /

Dottore di Ricerca in Civil and Environmental Engineering

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Submitted on	28.02.2017
Oral examination on	08.05.2017
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2017

To my mother, who has taught me that constancy and perseverance are the keys to achieving our dreams, for her constant support and her infinite love.

THESIS OUTLINE

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1. SUMMARY

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In the last decades, the surveying field has benefited from some major advances. Upon their introduction, laser scanners have revolutionized the surveying world, gradually establishing as a basic tool, at first for terrestrial and later for airborne surveys. At about the same time, photogrammetry also experienced its own evolution, as the concept of Structure-from-Motion (SfM), introduced in the late 1970s (Ullman, 1979), rose to popularity with the work of Snavely, et al. (2006). Structure from Motion (SfM) and MVS (Multi-View Stereo) algorithms generate very dense 3D colour point clouds, quite similar in size to those produced from laser scanning surveys.

However, these procedures may not always be considered reliable. In fact, matching algorithms can be very sensitive to data collection and illumination differences and not reliable in poorly textured or homogeneous regions. This can result in noisy point clouds and/or difficulties in feature extraction. Matching algorithms can also suffer from variable precision, strongly dependent on the pattern present on surveyed objects, as well as the difficulty of having control of the achievable accuracy at the geometric and morphological levels (Bevilacqua, et al., 2016).

On the other hand, due to the ability of SfM and MVS algorithms to generate 3D models with very little user input and to major improvements as to ease of use, their scope is extending beyond photogrammetry. However, high automation levels require caution because, while allowing for quicker modelling, control and perception of the steps to follow become looser, in some cases generating models that may look correct but lack morphologic or chromatic accuracy.

Taking into account these factors, it was deemed appropriate to investigate use of "black box"[1] software, considering the methodology for quality control not only of the final model but also during the different steps in the semi-automatic process.

Moreover, in terrestrial surveys, accessibility can still present challenging issues, where both Terrestrial Laser Scanning (TLS) and terrestrial photogrammetry are not viable options. Many situations, such as slanted roofs, domes, areas near ravines, etc., do not allow acquisition of both images and TLS data, necessary to generate 3D models. A solution of this problem is a new technique for the acquisition of photogrammetric data, based on the use of Unmanned Aerial Vehicles (UAVs).

Within the broader field of study of SfM-MVS techniques, this thesis focuses on four aspects in order to provide an operating methodology for surveys related to architecture

[1] Term used to describe software where users do not have sufficient control, if any, on processing parameters.

and cultural heritage: 1-Influence of number and position of Ground Control Points (GCPs) and tie points in SfM and MVS techniques; 2-Best methods for survey assessment; 3-TLS/SfM-MVS integration; 4-Original applications in architecture surveys. Besides, introduction of UAV-based applications has been investigated in some cases.

Guidelines for survey optimization, as well as methodologies for accuracy checks and data integration have been provided in the thesis, and also helped defining a workflow which has enabled the devising of original applications in architectural and cultural heritage contexts.

The tests reported corroborate several aspects:

While overall model accuracy is to some extent directly related to the number of GCPs and of images, tests carried out during the development of the thesis allow to point out some clarifications. It is possible to state that “more” does not necessarily translate to “better”, and that it is therefore most important to plan photogrammetric surveys so that any object appears on approximately 6 photos, each of which also shows at least 3 GCPs.

On the other hand, in rapid survey, the GCPs can be identified by on-site details, rather than marked with dedicated targets, and their layout can be affected by logistical constraints. Although this can save costly operations, they are, on the other hand, more prone to errors related to a difficult and less accurate collimation on the images. Therefore, it can be stated that whenever possible, the use of *ad hoc* targets is always advisable for the achievement of the planned accuracy degree; otherwise, the loss of accuracy due to the use of natural targets must be taken into account.

As for tie points, it should be remarked that user selection is not always necessary, since different tests on case studies have shown that software-selected tie points enabled the achievement of adequate accuracy levels. However, concerning manual input of tie points to a model calculated with some GCPs placed heterogeneously due to emergency and inaccessibility of the building, it is possible to state that higher number and homogeneous layout of the tie points entail higher-quality modelling.

Generally, after automatic feature extraction and matching, which enable tie points selection, it is necessary to ensure that the points are correct, in sufficient number and homogeneously laid out. Otherwise, user selection of tie points is necessary before dense point cloud calculation. In the next step, i.e. dense point cloud processing, a comparison is already possible between the methods commented in section 4.2 (Best methods for survey assessment).

In the aspect of Best methods for survey assessment, different possible data comparison types have been tested, without introducing new methods or improving existing ones, but rather suggesting a methodology covering each one of the 4 points described in the thesis in order to obtain a well-structured complete process. It is important to analyse each aspect individually, even if it is ultimately part of a whole.

Regarding TLS/SfM-MVS integration, the tests pointed out that the suggested methodology allows obtaining a three-dimensional model retaining the geometric precision of TLS surveys along with the texture quality attainable with a photographic survey campaign.

On the other hand, the ability of integrating photogrammetry and TLS allows obtaining more inclusive models in cases where time, safety or cost constraints prevent full accessibility to the survey object. The introduction of UAV-based techniques greatly reduces security risks by allowing access to otherwise non-accessible areas. Results presented show how, in case of necessity due to emergencies, integrating TLS with UAV-based photogrammetry can be a most effective option.

All these solutions allow to conclude that the proposed methodology allows to obtain solutions with greater productive efficiency considering all limitations of both TLS and SfM-MVS techniques.

Finally, the different studies carried out during this thesis provide a solution to the different problems faced in the case studies. As an example, the vault case presents a real problem whose solution saved many hours of work.

On the other hand, thanks to survey integration it was possible to obtain the current situation of the buildings, each presenting major security problems, and develop models to create an action plan for further intervention. The ability to map pathological conditions allowed for their quantification and analysis directly in the office without having to spend time in the field, in many cases in unsafe conditions.

Anyway, it is possible to conclude that a new workflow has been defined, where integration of the aforementioned research aspects has allowed to achieve an optimized survey, providing accuracy checks of the acquired data and integration of data from different sources, as well as accuracy controls of both each single-technique model and models obtained through technique integration.

Accurate analysis of these four aspects allows to define guidelines for low-cost terrestrial and UAV-based photogrammetry, which in turn enable generation of a workflow intended for use by any figure involved in surveying in architectural and cultural heritage contexts.

2. INTRODUCTION

2. INTRODUCTION

In the last decades, the surveying field has benefited from some major advances. Some years ago, introduction of laser scanners revolutionized the surveying world. The innovative technology allowed the acquisition of very large amounts of data in a short time: each scan generated a point clouds, with distance and angular measurements for each point. Depending on the scanner type, it could obtain details under 1cm (Time of Flight), close to 1mm (phase shift) or even more precise, 100 micron (triangulation scanner), eliminating the problem of long field times and allowing to obtain an amount of information hardly obtainable with classical acquisition systems.

Laser scanning enabled transitioning from sets of discrete points to high-density point sets (so-called point clouds). Previously, surveys were carried out by operators on individual points, collimated one by one according to selection criterions established before the actual survey phase. Survey correctness was linked with the skills of surveyor in the selection of the most significant points (in terms of both position and quantity) in order to correctly represent the geometry of architecture and landscape, based on the accuracy required. In this case, the geometry between two surveyed points was unknown. High-density surveys, although possible, had very high requirements for both costs and times.

Laser scanning changed the situation dramatically. The problem of the impossibility of choosing specific measure points was balanced by the availability of regular grids (2D / 3D) which allowed metric knowledge. In the planning phase, point selection was replaced by sampling size setting, shifting the focus from points to grids. While the coordinates of any given point in the surveyed area were not measured, the methodology allowed uniform collection of metric data from the surveyed object by reconstructing geometry information of the object as a whole. In addition, the introduction of built-in cameras added colour information to the high-density point clouds.

Thus, laser scanners gradually became a basic surveying tool at first for terrestrial and later for airborne surveys.

At about the same time, photogrammetry also experienced its own evolution, incorporating digital technology; anyway, this innovation had at first little impact on the overall performance, as the typical workflow of photogrammetric surveys still featured a low degree of automation. Although the restitution phase followed up its development towards simplification and automation, image acquisition was still constrained by the restrictive rules of classical photogrammetry, which force the formation of regular strips and photogrammetric blocks with rigid geometries (Kraus, 1994, Kraus, 1997, McGlone, et al., 2004).

A few years later, the concept of Structure-from-Motion (SfM), introduced in the late 1970s (Ullman, 1979), rose to popularity with the work of Snavely, et al. (2006). SfM and Multi-View Stereo (MVS) methods refer to sets of algorithms, derived from computer vision science, that assist photogrammetry by metrically estimating 3D structures through software-driven detection and matching of features across multiple images. These methods provided an addition to photogrammetry that allowed it to catch up with laser scanning, thus establishing the concept that in this work will be referred to as "new photogrammetry".

The new photogrammetric methods and algorithms are implemented in several software packages, each featuring its own approach as to SfM/MVS-Photogrammetry solutions and user interaction.

There are two main categories of SfM software (Shervais, 2016) (table 2.1):

- Commercially available software, for which the workflow is more streamlined but the interface generates the so-called "black box" effect, i.e. users do not have sufficient control, if any, on processing parameters.

- Open source/scientific software, for which the degree of control of processing parameters is linked to workflow complexity and programming skills requirements; programs may need to be used in sequence and sometimes lack a graphical user interface.

Software	Commercial or open source?	Low density PC[1]	High density PC[1]	Georeference; mesh and texture	Notes and/or extra capabilities
Agisoft Photoscan Pro	Commercial	✓	✓	✓	Primary commercial software used in geoscience and archaeology.
Bundler	Open source	✓			Creates output file of camera locations and low density point cloud; can be input into PMVS2 using "Bundle2PMVS2" script
CloudCompare	Open source			✓	Use for georeferencing output from CMVS + PMVS2
CMVS + PMVS2	Open source		✓		If easier to run from a GUI, use VisualSFM (GUI using same algorithms)

[1]PC = Point Cloud

Software	Commercial or open source?	Low density PC	High density PC	Georeference; mesh and texture	Notes and/or extra capabilities
JAG3D	Open source			✓	Add ground control points and apply transformation matrix to georeference; works with MeshLab output
MATLAB	Commercial			✓	Add ground control points and apply transformation matrix to georeference. Also can build mesh.
MeshLab	Open source			✓	Creates and textures meshes; can remove outlier points
PhotoModeler Scanner	Commercial	✓	✓	✓	PhotoModeler software optimized for UAS collection methods
Photosynth + SynthExport	Commercial (free for non-commercial use / open source	✓			Fast, but only produces a relatively low resolution model. SynthExport is needed to export the model.
Pix4Dmapper	Commercial	✓	✓	✓	Specifically for UAS collected data
Points2Grid	Open source			✓	Grid aligned point cloud to DEM
SFMToolkit3	Open source	✓			Uses SIFT algorithm to identify keypoints between photos
VisualSFM	Open source	✓	✓		GUI for CMVS +PMVS2
123D Catch	Open source	✓		✓	Low resolution textured 3D

Table 2.1. Comparison of multiple software platforms, both open source and commercial, for Structure from Motion applications (Shervais, 2016)

In recent years, a common trend of many SfM software houses is to develop products aimed at processing unordered collections of images, with a friendly interface, with more and more simplified procedures (single button) that facilitate the use of this technique by non-specialists and enable almost anyone to apply SfM to their data.

In Photogrammetry, accuracy and reliability of image orientation and camera calibration significantly influence the quality of all subsequent processes such as 3D point determination and 3D modelling (Remondino, et al., 2012).

The term "image triangulation" usually means the procedure followed to orient a set of images in order to derive exterior and eventually interior parameters. The procedure requires a reliable set of image matches (tie points), manually or automatically extracted, which are the main input for a subsequent non-linear least squares minimization, named "bundle adjustment" (Kraus, 1994, Kraus, 1997, McGlone, et al., 2004).

Automatic feature extraction and matching enable extraction of the homologous points.

The accuracy in the automatic extraction of homologous points depend on several factors, such as the operator for the interest point detection, presence of convergent images, unpredictable baselines and scale variations, lighting changes, homogeneous textures, repetitive patterns, complex object configurations, nearly planar scenes, etc.

Currently, due to the ability of SfM and MVS algorithms to generate 3D models with very little user input and to major improvements as to ease of use, their scope is extending beyond photogrammetry. However, high automation levels require caution because, while allowing for quicker modelling, control and perception of the steps to follow become looser, in some cases generating models that may look correct but lack morphologic or chromatic accuracy.

Currently, photogrammetry has gained back the outstanding position within the medium- and large-scale survey field, which went lost in past years. In order to avoid the black box effect, developers have started to provide geomatics and/or photography operators with the operating details of some algorithms, such as shape recognition and camera parameters calculation. Although this opening does not yet apply to most of the processes involved, a trend is recognizable for enabling ever-increasing user control over task automation (Martínez-Espejo Zaragoza, 2014).

Taking into account these factors, the candidate deemed appropriate to investigate use of black box software, considering the methodology for quality control not only of the final model but also during the different steps in the semi-automatic process.

While the benefits of active sensors are undeniable, at the same time professional or qualitative improvements of photogrammetry algorithms are redefining cost/quality ratios, so the balance can shift from case to case (table 2.2). In spite of this, it is clear that integration of both techniques is often the best solution to correctly and completely collect geometric and radiometric information of the studied object.

In this regard, an extract by Ackermann (1999) is reported:

"The systematic combination of digital laser and image data will constitute an effective fusion with photogrammetry, from a methodical and technological point of view. It would

resolve the present state of competition on a higher level of integration and mutual completion, resulting in highly versatile systems and extended application potential. A total fusion would certainly agree with the general trend towards universal multi-sensor and multi-data systems."

	Photogrammetry Image-based Modelling	**Laser Scanner 3D** Range-based Modelling
Features:		
Equipment cost	moderate	high
Ease of handling	excellent	sufficient
Times for data acquisition	smaller	greater
Times for modelling	long	Sometimes very long
3D Information	to derive	directly
Distance dependence	Independent	Dependent
Dimension dependence	Independent	Dependent
Material dependence	Independent	Dependent
Dependence on ambient light	Dependent	Independent only for ToF system
Geometry dependence	Strongly dependent	Independent
Texture dependence	Dependent	Independent
Scale	Missing	Implied (1:1 with real data)
Data generated volume	It depends on images resolution and measures type	Dense point cloud
Modelling of fine detail	good / excellent	Excellent
Texture	Included	Missing/ low resolution
Survey of edges	Excellent	Quite problematic
Quantitative / statistics analysis	for each point calculated	Global
Open-source software	Few	Very few

Table 2.2. Main features of photogrammetric and 3D laser scanner techniques (adapted from Russo & Remondino, 2011).

Since this thesis focuses on low-cost surveying, a part of the related research work dealt with TLS/SfM-MVS integration for cost reduction purposes.

Moreover, in terrestrial surveys, accessibility can still present challenging issues, where both Terrestrial Laser Scanning (TLS) and terrestrial photogrammetry are not viable options. Many situations, such as slanted roofs, domes, areas near ravines, rough and dangerous terrain, areas with very little available space, etc., do not allow acquisition of both images and TLS data, required to generate 3D models. A solution of this problem is a new technique for the acquisition of photogrammetric data, based on the use of Unmanned Aerial Vehicles (UAVs).

This thesis focuses on some aspects of Image-based modelling techniques, which are currently the topic of several studies: (a) influence of number and position of Ground Control Points (GCPs) and tie points[2] in SfM and MVS techniques, (b) best methods for survey assessment, (c) TLS/SfM-MVS integration and (d) original applications in architectural surveys. Besides, introduction of UAV-based applications has been investigated in some cases.

(a) A thorough investigation of SfM-MVS techniques required taking into account several factors. Although technology innovation has allowed to forgo the rigidity of classic photogrammetry and generate eye-catching models with reduced user input, it must be pointed out that this achievement in itself does not entail better results as to accuracy, precision and texture quality. Therefore, it is important to carefully consider which factors influence precision and accuracy of the survey, such as GCP and tie point distribution, manual tie points influence, image selection, use of GCPs in the bundle adjustment process, etc. Thus, one of the innovative points deemed as appropriate is the investigation of all the factors enabling control of the steps to follow in black box SfM software, because, while new photogrammetric techniques allow to achieve familiar-looking results almost automatically, it is important to define guidelines allowing to retain a certain control over the software and obtain optimized results in terms of both looks and geometric accuracy.

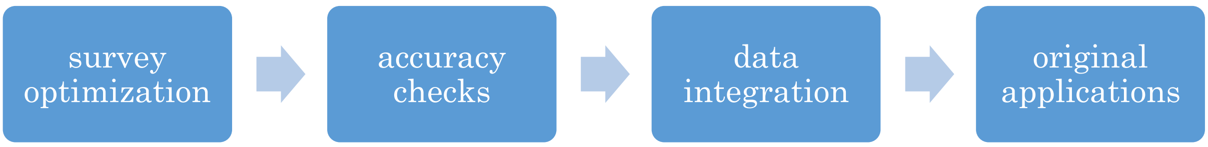
(b) It is often necessary to verify the accuracy of the survey, in some cases to investigate the possibility of integration of some techniques, in others to check its correctness, or to compare the evolution of the surveyed object in time. Whatever the purpose, it is interesting to analyse the types of possible comparisons and which one is the most appropriate for each case. The main kinds of methodology for data comparison are Actual object - Virtual model, Virtual model – CP and Virtual model – Virtual model. While each comparison method is often viable, in some cases one or two methods are not usable. Some case studies were carried out in order to show and analyse these methodologies. Rather than introducing new methods or improving existing ones, the following investigation of the possible comparison methods aims at defining a methodology including each one of the 4 points described in the thesis so to obtain a well-structured complete process. It is important to consider each aspect individually even if it is ultimately part of a whole.

(c) During the progress of this thesis, several cases needed integration in order to achieve complete results with the required resolution. The study of Image- and Range-based modelling techniques shows how models generated by the integration of both techniques carry the benefits of both, such as meshes with high quality and uniform

[2] Definitions of GCP and tie point are given in section 4.1

accuracy (by TLS) and high-resolution textures (by photogrammetric techniques). This is the case when both techniques are used in the respective optimal conditions. In other cases, integration is a requirement in order to complete surveys presenting parts covered by only one of the two techniques, due to either physical constraints (e.g. accessibility issues) or limitations of the technique (e.g. lighting and/or texture issues, etc.). The goal is offering a methodology in order to obtain solutions with greater productive efficiency considering all limitations.

(d) Application of SfM/MSV techniques is particularly effective for the analysis of historical buildings, in particular of special architectural complexes hardly detectable through traditional techniques. The possible integration of these techniques with laser scanning generates new possibilities, such as the detailed study of objects at morphological and chromatic levels, the study of pathologies on a large scale and so on. Moreover, with the introduction of UAVs, surveys in emergency or risk areas, as well as areas with accessibility issues, have become possible with no negative consequences on operator safety. All these possibilities are presented as original applications of these techniques. The aim, in this case, is the definition of a new workflow, where integration of the aforementioned research aspects allows to achieve an optimized survey, providing accuracy checks of the acquired data and integration of data from different sources, as well as accuracy controls of both each single-technique model and models obtained through technique integration. This allows to offer some application solutions taking advantage of each technique in architectural and cultural heritage contexts.



In order to study these research aspects, several case studies that allow the implementation of what was first discussed in theory have been selected.

The case studies where these aspects have been applied are listed below (table 2.3):

- Palazzo Roncioni Vault (Pisa, Italy)
- San Miniato church (Pisa, Italy)
- Harzburger Hof hotel (Bad Harzburg, Germany)
- San Francesco church (Ferrara, Italy)

	Palazzo Roncioni	San Miniato	Harzburger Hof	San Francesco
Influence of GCPs/tie points in SfM and MVS techniques	✗	✓	✓	✗
Best methods for survey assessment	✓	✓	✓	✗
TLS/SfM-MVS integration	✓	✓	✓	✓
Original applications in architecture surveys	✓	✓	✓	✓

Table 2.3. Relations between case studies and objectives

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3. STUDY OBJECTS

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As stated in the previous chapter, the analysis of the essential aspects of this thesis involved several case studies, which the candidate has investigated in association with the ASTRO laboratory (*Applicazioni Scientifiche Topografiche per il Rilievo Operativo* - Scientific topographic applications for field survey) of the Department of Civil and Industrial Engineering, University of Pisa. The following paragraphs list each case study object, along with some useful information for their contextualization and with the description of the techniques exploited in surveying and data processing.

3.1. PALAZZO RONCIONI VAULT (PISA, ITALY)

The object of the first case study is located in Pisa, and has been investigated by the candidate in collaboration with ASTRO Laboratory. Results from its investigation are included in three articles published during the thesis period of the candidate: Martínez-Espejo Zaragoza, et al., 2014, Caroti, et al., 2015A and Bevilacqua, et al. 2016.

The study object is a frescoed vault on the ground floor of Palazzo Roncioni, in Pisa (fig. 3.1). The vault is a type rather common in Italy known as *a schifo* or mirror vault, having a not quite regular rectangular plan. The height from the floor to the top of the vault is about 6m. The fresco, painted by Tuscan painter Giovan Battista Tempesti, is largely preserved, though it presents some obvious recent gaps due to environmental degradation. The vault also shows widespread injury due to a failure of structural nature.

Figure 3.1: frescoed vault, Palazzo Roncioni, Pisa

This research proposes an alternative way to obtain textured models with high quality levels for geometry, morphology and colour that takes advantage of the strictness of 3D models produced from Terrestrial Laser Scanning (TLS) surveys, and of the quality of textures derived from sets of photograms oriented with dedicated SfM and MVS algorithms.
The basic concept is to use TLS surveys as the geometric foundation. Regarding the texture, a campaign of dedicated photographs is completed and, rather than orienting and projecting each one individually, SfM and MVS techniques are used not so much for the model that it generates, as for its ability to automatically detect numerous sets of homologous points and to solve the problem of calculating the orientation parameters (camera features). Finally, the model generated by the TLS survey is imported in the same SfM and MVS software used for camera orientation and the images are projected on it. As a case study for this methodology, the frescoed vault has been chosen.

TLS survey

Leica Geosystems' C10 ScanStation has been used at two spots, located approximately 1/4 and 3/4 lengthwise and both along the centre across the room (fig. 3.2 left). The resolution of the survey was set at 4mm at 10m, resulting in a very dense cloud (on average 70pts/cm^2). The point cloud is in true colours due to the scanner's built-in camera.

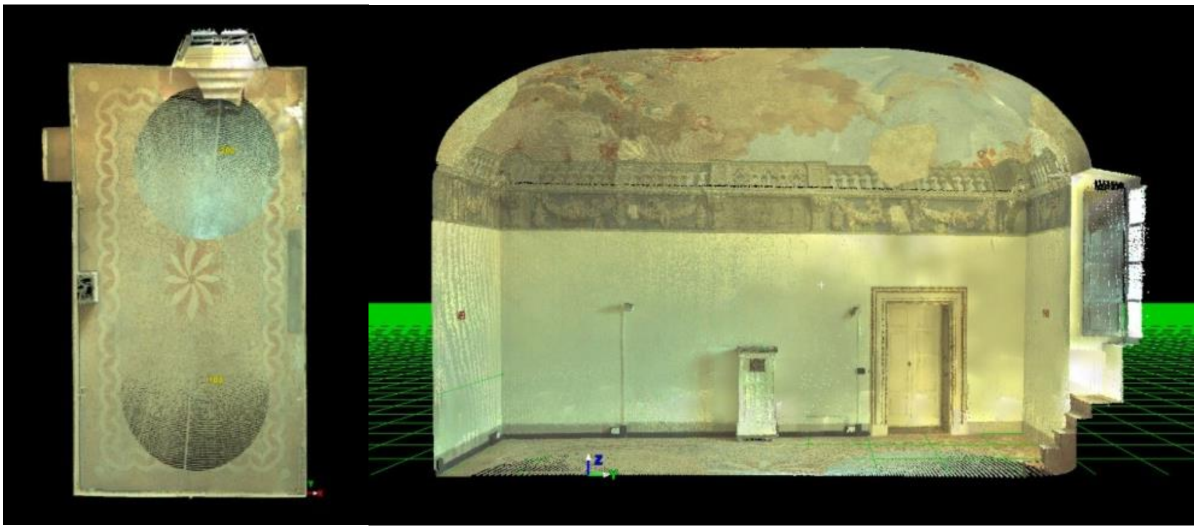


Figure 3.2: Plant (left) and geometric reference model derived from TLS survey (right)

After scans have been aligned by means of a support traverse, aided by the cloud constraint tool in the Cyclone software environment, the cloud point was processed by a reverse modelling software (Inus Technology Rapidform XOR3). In order to simplify the model where surfaces were smooth, a decimation of the points was performed (preserving detail in regions with greater curvature radii), anyway preserving geometrical information that, however small, are valuable for restorers (local deformations, cracks, and so on); finally, a mesh was generated. The model includes about four million points and ten million triangles and is the geometric and morphological reference of the final model (fig. 2.2 right).

Photogrammetric survey

The photographic survey was performed with a Nikon D700 SLR camera equipped with a focal length 20mm Nikkor lens. ISO sensitivity set to 400 enabled shooting at 1/25 second with 5.6 aperture, also thanks to the lighting provided by a set of two 2000 W halogen lamps with colour temperature of 5600K. The shooting distance was on average of 4.5m, which allowed single pixel coverage of about 2 mm. The camera and its lens have been previously calibrated. Table 3.1 shows the features of the camera and the results of the calibration.

Focal length	[mm]	20.62
Format size	[mm] [pixel]	36.00x23.95 4256x2832
Principal point	[mm]	X=17.95 Y=12.34
Lens radial distortion coefficient	K_1 K_2	2.876e-004 -4.817e-007
Overall residual RMS[3]	[pixel]	0.0854

Table 3.1. Sensor features and calibration parameters

Generation of the model through the SfM and MVS techniques was achieved by means of a dedicated photogrammetric campaign with an overlap between photograms of 70% in both directions. The SfM and MVS software used in this test was Agisoft's PhotoScan 1.0.0. The development followed the steps provided by all software of this type: camera calibration, image orientation, dense point cloud generation, surface generation and texture mapping and visualization (Manferdini and Remondino, 2010).

The result of processing is a 3-D, high colour resolution model (fig. 3.3 left), albeit with a lower quality mesh as for morphology and geometry (fig. 3.3 centre) compared to that obtained from processing of the TLS survey (fig. 3.3 right).

[3] Root Mean Square

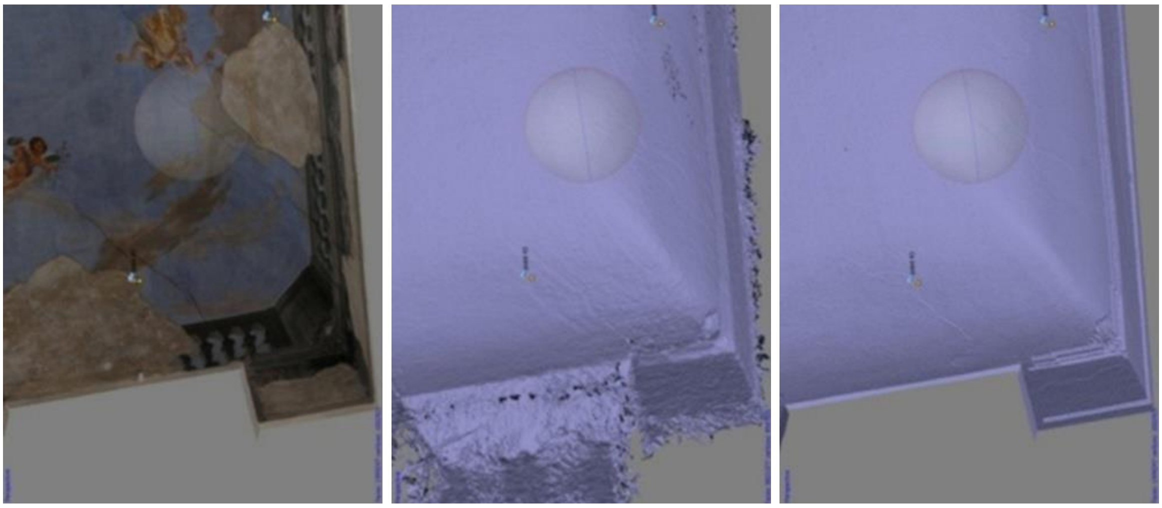


Figure 3.3. Texture from SfM and MVS (left), SfM-MVS model (center) and model from TLS (right)

3.2. SAN MINIATO CHURCH (PISA, ITALY)

The second case study is located also in Pisa, but in a village on the outskirts of the city. Results from its investigation are included in two papers during the thesis period of the candidate: Martínez-Espejo Zaragoza, et al., 2015A and Caroti, et al., 2015B. In this case study an UAV was used in order to carry out the inaccessible area of the church.

The survey object is San Miniato's church in Marcianella (Cascina, Pisa, Italy). It was chosen as test field for its small dimensions, the presence of survey elements at different levels and its placing in a secluded, quiet area.

The church, in Romanic style, dates back to mid-to-late X century AD. It has a rectangular plan (20m x 7m x 8m, L x W x H) and two entrances, a secondary one on the South façade and the main one on the West façade, above which stands a belfry reaching at about 13m (fig. 3.4).

The interior is fully accessible and includes a single aisle. The exterior is easily accessible along the South and West sides, while the presence of trees and walls hampers access to the North and East façades, respectively.

Figure 3.4. San Miniato church, the main façade

In order to achieve a complete model of the church, different survey techniques were exploited. These include laser scanning for surveying the inside and outside of the church (with the exception of the extrados roof, not accessible); UAV-based photogrammetry, for surveying the main façade and roof; terrestrial photogrammetry, for the application of photorealistic texture to the laser scanning model; total station, to bind laser scanning and photogrammetry data with high precision. The survey of the same area (the main façade) with both TLS and SfM/MVS techniques, allowed in turn the control of the UAV-based photogrammetry, in which achievable accuracy is neither repeatable nor homogeneous. A total station survey measured the position of 67 Ground Control Points (GCPs) and Check Points (CPs) used to scale the model and to perform comparison and accuracy analysis of UAV-based photogrammetry.

Laser scanning

The TLS survey was performed with a Leica C10 Scanstation, a laser scanner with a built-in camera, and provided the base to achieve the complete model of the church. Eleven scans were performed in total, four inside (fig. 3.5, right) and seven outside the church (fig. 3.5, left), with a spatial resolution = 0.010m @ 10m and scanner positioning precision = 6mm, as stated by the manufacturer.

In the post-processing phase all scans were imported into the processing software and oriented in the same reference system. From the oriented point clouds, a three-dimensional high precision model was generated (3.73 million polygons mesh).

Figure 3.5. Laser scanning survey: outside (left) and inside (right).

Aerial photogrammetry from UAV

Images of roof and principal façade were shot by an UAV-borne camera (fig. 3.6). The aircraft used is a yet unmarketed prototype UAV, manufactured by Pisa-based CAM

(*Costruzioni Aero Meccaniche* - Air Mechanical Manufacturing), an industrial partner of the ASTRO Laboratory.

The camera used for the survey is a Nikon D600 SLR (35.9mm x 24.0mm CMOS sensor, 6016 x 4016 pixels), fitted with a fixed focal Nikkor lens (50mm, f/1.8), for a total weight of about 1.5kg. The camera shoots a photograph every second. Planned altitude and speed of flight resulted in a Ground Sampling Distance (GSD) of about 2 mm and a minimum image overlapping of 70%. In the case of the UAV used in the survey, maximum duration of each flight ensured by the on-board batteries is about 10 minutes. The UAV was remotely piloted by a specialist in two flight sessions (each one of about 4 minutes): one for the main façade only, and one covering the area of the main façade and the roof.

Common settings for both sessions:

- f11 aperture priority, 1/800 – 1/1000 shutter speed;
- Flight speed ≅ 2m/s, with calculated Image Motion Compensation Distortion < 1 pixel;

These settings enabled to detect the same point on at least 3-4 images, also granting a good configuration for subsequent processing with SfM-MVS algorithms.

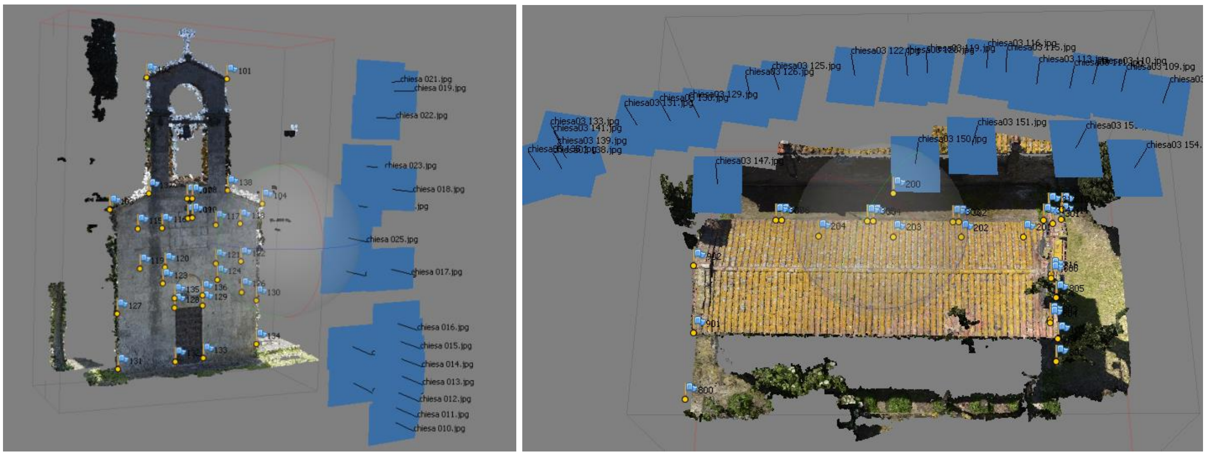


Figure 3.6. Roof and principal façade survey performed by an UAV-borne camera

In these surveying conditions, aircraft and camera were about 27m above GCPs on the ground, 20 m above GCPs on the roof and 14.5 m above those on top of the belfry, with a GSD of 3.2mm, 2.4mm and 1.7mm respectively.

Survey of the main façade included two vertical strips, at an average distance of about 15 m from façade and GCPs, with a GSD of about 1.8 mm.

Data were processed with SfM-MVS techniques, using Agisoft's PhotoScan software, a well-known product in both scientific and technical fields. Two separate models were obtained, for the roof and the façade.

The roof model was generated by processing of a set of 36 pictures and allowed completion of the TLS model. The façade model was generated by processing of a set of 18 pictures and allowed comparison of TLS model against that derived from SfM-MVS applied to UAV-borne photogrammetry.

Reference measurements

In order to collect the reference measurements, a support topographic network was established by means of a Leica Geosystems' TPS1201+ total station. It included 4 survey markers, from which 57 GCPs, on the ground and on the building, were measured. The layout of the GCPs is as follows:

- 11 on ground;
- 31 on the façade, evenly distributed at different levels;
- 15 on the roof, of which 9 along the eaves, 1 on top and 5 on top of the bell tower.

After processing the topographical measures, point coordinates were framed in a reference system with the X-axis parallel to the main façade; consequently, direction of the Y-axis is East and subparallel to flight direction and main axis of the building. Z coordinate acts as relative elevation. This network of control points provided a point set whose coordinates were assumed as reference for accuracy checks on the models; besides, it allowed exact registration of each survey in a single reference system.

3.3. HARZBURGER HOF HOTEL

This case study originated during an internship of the candidate at the *Institut für Geodäsie und Photogrammetrie (IGP)* at the *Technische Universität Carolo-Wilhelmina zu Braunschweig* (TU Braunschweig). Every relevant field operation was carried out from a collaboration between the IGP and the Institut für Flugführung (IFF), also of TU Braunschweig (Martínez-Espejo Zaragoza, et al., 2017).

The present case study refers to Harzburger Hof, a wooden luxury hotel built in 1874 in Bad Harzburg, a spa station in Germany (fig. 3.7).

In May 2014, a fire burst out in the southern body, quickly extending to all floors; as a result, the whole structure became unstable and the immediate surroundings unfit for use.

After a few weeks, researchers of the IGP carried out a 3D survey campaign of the involved area (about 8 hectares) in order to produce metric documentation of the *status quo ante*. The candidate has subsequently gained access to all survey data.

Figure 3.7. Test area

Survey methodologies

Surveying operations exploited the following geomatics techniques:

- Terrestrial laser scanning (TLS);
- UAV-borne photogrammetry with horizontal flights.

Use of multiple surveying methodologies was required in order to allow, upon integration of the different surveys, achieving a complete dataset of the whole complex in spite of the difficulties entailed by the disaster. This has also highlighted the many problems arising when applying these methodologies to dangerous, precarious areas.

Three scans have been performed outside the hotel using a Riegl Vz1000 terrestrial laser scanner: two on the front, henceforth referred to as L1 and L2 respectively (fig. 3.8), and one on the back, with a mean distance of roughly 40m and resolution just about 2cm. The scans have been provided in "*.pts" format, which also includes intensity values for each point.

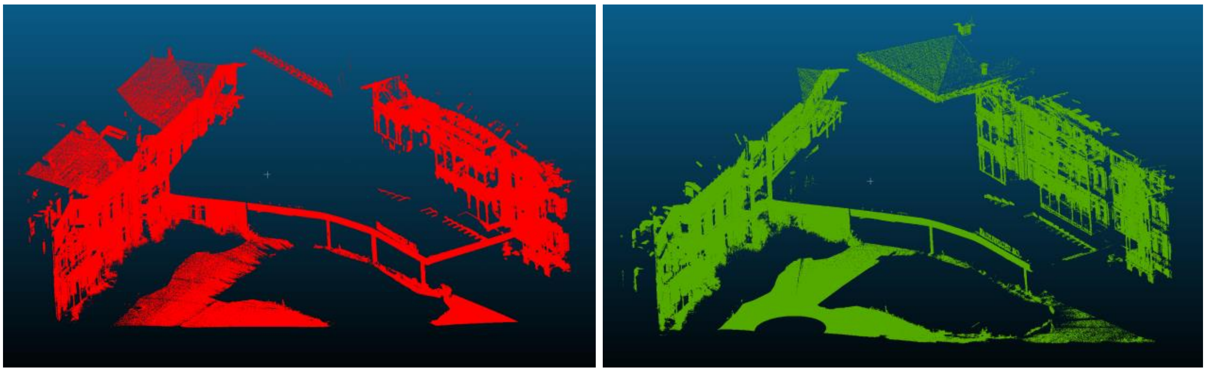


Figure 3.8. L1 (left) and L2 (right)

Airborne imagery has been collected by a Canon IXUS 220HS digital camera, whose specifications include 35mm equivalent optics, 12.1Mpx backlit 1/2.3" CMOS sensor and weight = 141g (with battery and memory card). The camera was mounted as payload on an AirFrame F450 multirotor, fitted with an APM 2.6 Autopilot system and GPS.

Planning for UAV-based data collection provided for image shooting along horizontal strips with pseudonadiral axis, collecting 886 images during a 7 minutes flight; mean flight level was approximately 45m with Ground Sample Distance (GSD) close to 1.74cm/px and 85% overlap along both axes. Mission Planner 1.3.7 software handled flight path management (fig. 3.9).

Figure 3.9. Planning for UAV-based data collection

In order to achieve a 3D model of the *status quo ante* of the exterior by integrating survey methodologies, the coordinates of some Ground Control Points (GCPs) were measured in the field (fig. 3.10). GCPs have been identified by markers or studs and laid out both at ground level and on the building, according to the access restrictions imposed on the survey area. Measures have been carried out by both total station and Global Navigation Satellite System (GNSS) receiver in order to overcome the obstacles and logistical problems facing the operators in the survey area.

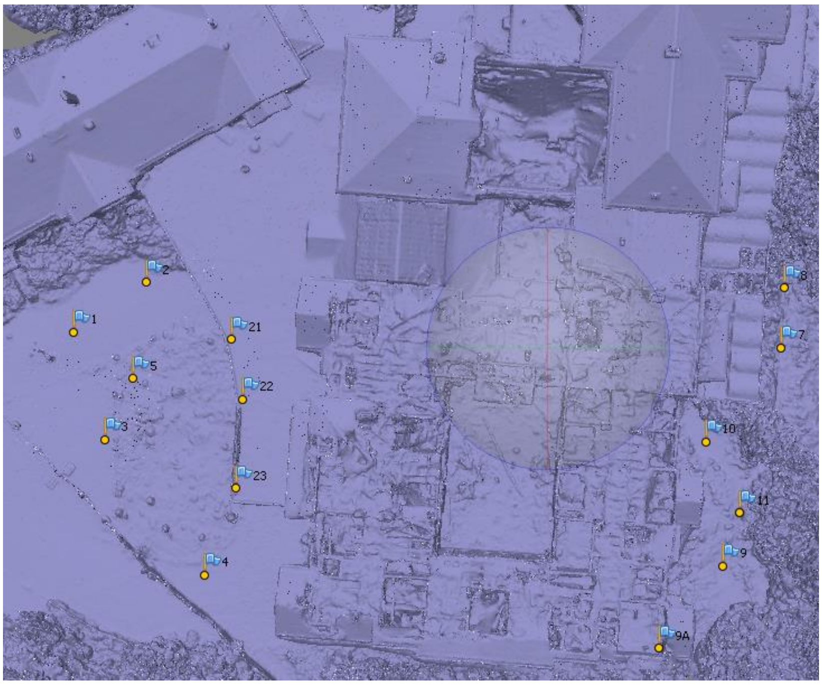


Figure 3.10. GCPs layout

Total stations have been set up near the main entrance (west side) and in the park area on the back (east side), using a Leica TS02. Since there was no mutual visibility between positions and no points could be sighted from both stations, they have been linked via GNSS RTK methodology.

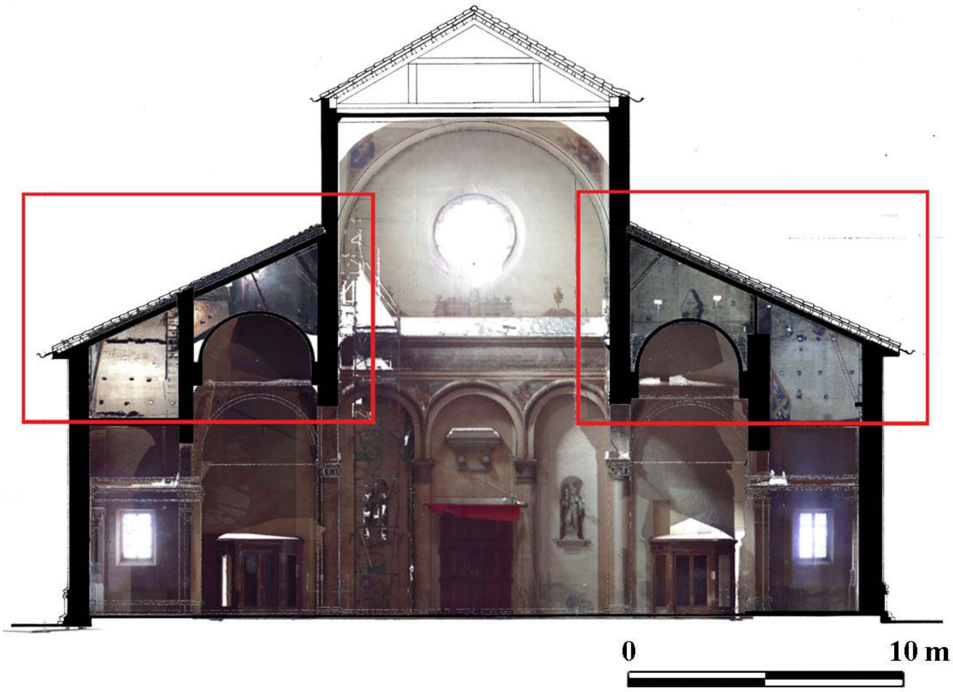
3.4. SAN FRANCESCO CHURCH (FERRARA, ITALY)

This case study originated from a collaboration between ASTRO and Hera, a Grosseto-based surveying firm (Martínez-Espejo Zaragoza, et al., 2015B) in order to work in a church affected by an earthquake.

San Francesco Basilica, located in the old town of Ferrara, was built in 1494 on a pre-existent building (possibly a XIV century Gothic church), already in use by the Franciscan order, based on a draft of architect Biagio Rossetti, as commissioned by Duke Hercules I as part of an effort to revitalize and modernize the old core of the city. The volume of San Francesco, then, was shaped by Rossetti to streamline a number of road nodes of medieval Ferrara (Zevi, 2006).

Throughout its history, the basilica has gone through several cycles of damage and recovery: in particular, it suffered damages and structural failures following a seismic event in May 2012. A new plan for recovery and preservation of the main aisles was drafted, focusing in particular on the domes and chapels of the side aisles of the Basilica, aiming at the achievement of three-dimensional models for the exterior and interior aisles, with particular attention to their attics, and for the bell tower.

The study object investigation involved the survey of the attics of the four side aisles, which, at the time of the surveying operations, showed severe damage (fig. 3.11). The attics of outer aisles measure 46.25 m (length) x 4.42 m (width), while their height varies from 3.95 m to 6.25 m; each one contains the extradoses of eight barrel vaults (radius = 2.8 m), and at the time was accessible by mean of narrow wooden walkways that allowed longitudinal movement. The attics of inner aisles measure 46.25 m (length) x 5.46 m (width), with height varying from 3.80 m to 5.50 m, and each one contains the extradoses of eight domes (radius = 2.37 m). Their surveying has been particularly challenging, due to presence of obstacles that greatly reduced available operating space; in fact, the imposts of adjacent domes are quite close (about 30 cm) and merge into the perimeter walls, effectively precluding movement of persons and gear.



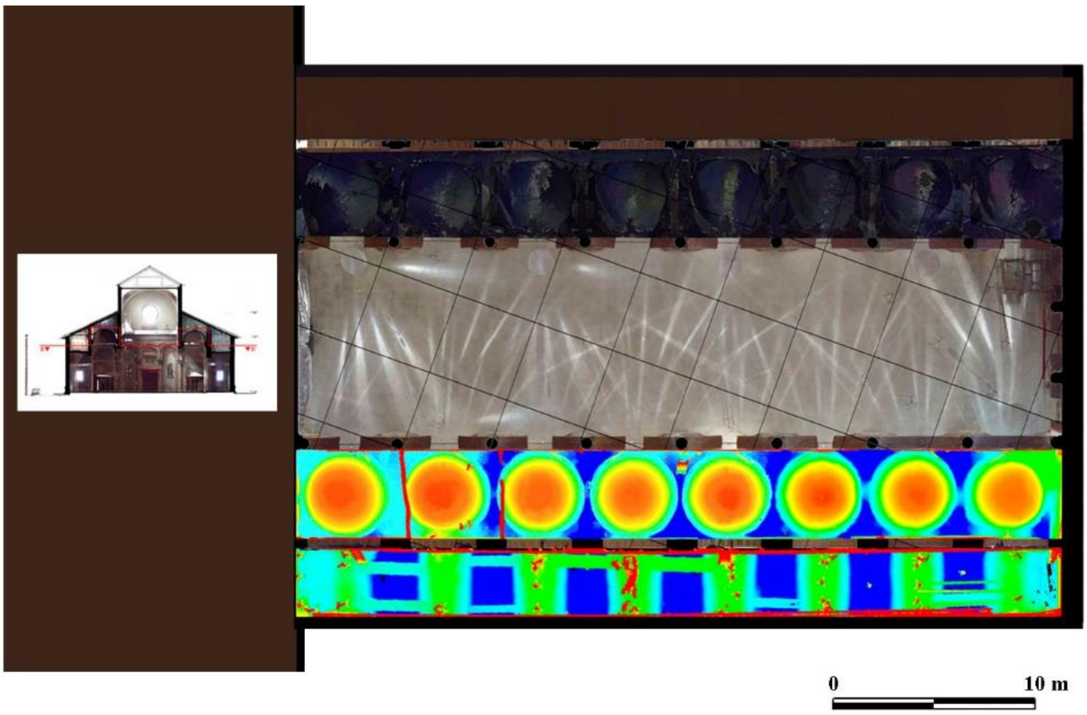


Figure 3.11. Cross (above) and horizontal (below) section of the aisles attic

At the time of the survey, the inner right-hand aisle was safe, with raised wooden walkways to allow movement. On the other hand, the outer right-hand aisle was inaccessible and therefore it was not surveyed.

Left-hand aisles were accessible, although lacking any intervention for debris removal or installation of wooden walkways. The extradoses of the domes are quite often broken, with entire rows of bricks missing in the worst cases.

The attics featured slanted beams along with horizontal, lower ones, both original and replaced during recovery interventions, which cause major shadowing issues as regards installation of artificial lighting sources. In order to overcome the problem by achieving a diffused light, a very high number of light points should be used, at least one every impost. Besides economic issues (generally a major limiting factor in the planning of a network), this solution further limits the available operating space, so that localized lighting was chosen instead, moving the floodlights together with surveying instrumentation. Floodlights used in this survey feature colour temperature control, which was set at 5400°K.

Surveying (3D data collection)

The attics of the aisles of the Basilica were surveyed with a Trimble TX5 laser scanner, fitted with a built-in camera. The resolution of the survey was set at 4 mm at 10 m, the merging resulting in a very dense point cloud (on average 100 pts/cm2). In order to simplify the model, a decimation of the points was performed on smooth surfaces (preserving detail in regions with greater curvature radii), preserving in any case the geometrical information.

In order to texture the derived model with more faithful colours, optimised for subsequent three-dimensional modelling via SfM and MVS methodologies, a dedicated photographic campaign was performed using a Nikon D800 camera fitted with fixed 50 mm and 24 mm lens.

Image collection

A theoretical photo-shooting plan requires compliance with well-defined parameters. In the present survey, movements were allowed at best only along narrow wooden walkways, which define the direction along which the base-to-range ratio can be granted as correct. As regards vertical shootings, the presence of beams and the operating difficulties preclude raising or lowering the shooting point. In the most inaccessible or unsafe areas, it has been sought to collect as many images as possible, dropping the optimal shooting design and leaving check and eventual deletion of unfitting photograms to the subsequent processing step.

Generally, for each room, photograms did not follow a fixed shooting plan, exploiting the interpretive abilities of SfM-MVS software. Many images have been correctly oriented (with crosschecks versus laser scanning data) only thanks to smart points automatically detected by the software. Other cases required manual input of the coordinates of several control points detected in the point cloud. The geometrical precision obtained is the order of 1 cm. On the other hand, the graphic resolution of the applied texture is higher and coincides with the linear dimension of the pixel, in the order of 1 mm. This allows reading of very small elements (e.g. rifts, cracks, deformations, etc.). In order to reduce shadowing issues, great care was taken to place the camera in the midpoint of the lighting sources covering the mid-upper and mid-lower portion of each photogram, respectively.

Laser scanning collection

Laser scanning resolution was set in drafting phase at 4 mm/10 m; each room was covered on average with 10 scans, each one requiring about 9 minutes. It was linked to a pre-existent topographical network via use of a total station.

Laser scans of the attics have also used artificial lighting, aiming to place the scanner in the midpoint between two floodlights.

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4. ASPECTS OF THE RESEARCH

4.1. INFLUENCE OF GCPs/TIE POINTS IN SfM AND MVS TECHNIQUES

As is well known and verified by various authors, SfM and MVS techniques consist of two parts: data collection, which includes camera calibration and network (planning and picture shooting) (Martínez-Espejo Zaragoza, et al., 2015), and data processing, which includes (Abdelhafiz, 2009, Manferdini & Remondino, 2010):

- used of bundle adjustment algorithms, for semiautomatic computation of parameters for external and internal camera orientation,
- 3D restitution and surface generation,
- quality analysis of results
- texture mapping and visualization.

Moreover, in order to generate models with high chromatic resolution and high geometric accuracy, well-defined conditions must be granted. Lighting must be homogenous, frame overlap must be greater than 70%, an ideal shooting base/range ratio (1/3 – 1/4) would be strongly advisable and image shooting should follow both normal and convergent imaging geometries.

Virtual models obtained by meeting these criteria are well proportioned, framed in an image reference system and have good chromatic resolution. Anyway, model scaling requires input of references points or distances, while framing a model in a real/absolute reference system can only be achieved upon input of reference points, which are therefore ultimately needed for accuracy investigations.

To this purpose, points used are essentially of three types (Martínez-Espejo Zaragoza, 2016, pp. 31):

Ground Control Points (GCPs): points with known coordinates in both the image system and the absolute system, used for metric model generation and geo-referencing (i.e., transferring the coordinates to a known reference system, e.g. mapping, local, etc.) and increasing geometric accuracy. In addition, they can be used to calculate external and/or internal camera parameters.

Even minimum requirement provided only three points, a higher numbers allow increasing accuracy and control. Distribution over the area of interest must be as homogeneous as possible.

Control Points or Check Points (CPs): points with known coordinates in both the image system and the absolute system, used for error checking to test model accuracy. They are not used to calculate external and/or internal camera parameters.

Tie points: defined only in the image system, so that absolute coordinates are unknown; input can be either automatic or manual. These are homologue points that help define the relation of the position between the photos.

A still unresolved issue in the investigation of SfM and MVS techniques is the definition of some properties of these points. Although literature provides several descriptive suggestions or advice on points use, distribution, size, etc., these lack any defining nature. Thus, the candidate deemed appropriate to highlight some relevant considerations and to investigate.

4.1.1. Number and disposition of GCPs

Ideal GCP settings provide for use of the minimum points as to ensure detection of at least three GCPs per image, marked with suitable targets and uniformly laid out around the object, at different heights or depths. Actual operations, based on the study of some examples and direct experience, do not meet such criteria.

Overall cost is a key factor in survey planning. Although SfM and MVS techniques, unlike TLS, are considered low-cost, it is important to consider GCPs as they could affect the price considerably. For example, accessibility issues in survey areas entail proportionate difficulties in the target placement, or in measuring natural points from accessible areas. On the other hand, for objects with highly relevant textures, it is also likely that anything covering the surface would hamper surveying operations. All these factors must be weighed up prior to drafting the target layout. It will also be necessary to consider the restitution scale to set the required accuracy level to acquire the data (Total Station, GPS, etc.). If the use of targets is not possible, natural points of the object may be chosen with the utmost care, because their ease of detection greatly affects overall accuracy. Besides, use of natural points also affects office time requirements due to collimation difficulties, possibly eroding any savings in term of time and costs in the data acquisition phase.

Another factor to consider is the use of GCPs in the bundle adjustment process; procedures involving their use are known as “Constrained”, while those forgoing the use of GCPs are known as “FreeNet”. Therefore, in Constrained processes the GCPs are used for calculation of the internal and external camera parameters as well as for georeferencing and scaling, while in FreeNet processes the GCPs are used for georeferencing and scaling only.

4.1.2. CPs as Check Points

As stated in section 4.1., CPs are only used for error checking in order to verify model accuracy. Therefore, these points are not strictly required to perform a survey. However, in this thesis they are of great importance since one of the topics of greatest interest is the study of the accuracy in the survey.

CPs can be marked up either by targets or natural features, and may not match GCPs, as the former are used for error checking for each single point, without spreading it as is the case for the latter. These points do not affect calculation of camera parameters, and their placement must be functional for accuracy calculation. Tolerance of surveying methods must also be taken into account, as well as markup type.

4.1.3. Tie points

As previously explained, tie points only have image coordinates, so their accuracy is not dependent on the instrument used to measure their coordinates.

SfM and MVS software automatically select this kind of points; however, user selection is also possible. In general, user-selected points have a higher weight than those selected by software. Manual collimation of tie points can influence the accuracy of the model. Differences between before and after input of these points can be dramatic, as shown in one of the case studies presented (Harzburger Hof). The need for tie points can change from case to case, increasing in case of heterogeneous GCP layout and/or insufficient GCP number.

4.1.4. Case studies

Although GCPs were used in almost all case studies, only in a few they have been analysed, as regards their influence on the accuracy of the study object. In the San Miniato church case, several factors were investigated as regards their effects on survey accuracy. These included user-operated point collimation, use of different numbers of GCPs, distribution of GCPs at different heights for surveys with several depth levels and use of GCPs for calculating internal and external camera parameters (Constrained or FreeNet).

In the Harzburger Hof hotel case study, several tests highlighted the influence of user-selected tie points in obtaining the final model. A first-model calculation relied on points calculated automatically by the software and on GCPs placed in accessible areas, directly on the ground or at the bottom of the building, which resulted in a highly heterogeneous layout. Subsequently, a second model was computed upon user input of tie points, homogeneously in selected across the model.

4.1.4.1. San Miniato church

This particular case (Caroti, et al., 2015) has been studied following a suitable approach for any operator lacking specific surveying experience, opting for a methodology in order to achieve a low-cost survey and entrusting UAV-related operations to a specialized company.

Rather than using target-based markup, features on the roof, façade and pavement surrounding the church were selected to identify CPs and GCPs in this context, allowing to overcome the logistic difficulties in placing targets at different levels. As an aside, this choice would also be the most common working option for standard operators.

This, however, led to greater difficulties in detecting and subsequently collimating points on the image, introducing collimation errors that affected the overall accuracy of the survey.

In order to take into account this problem and the need to process UAV-borne images in different modes, the same coordinate digitalization of GCPs and CPs were used for all processing.

In this way, possible digitalization errors affect all processing, much the same as a systematic error.

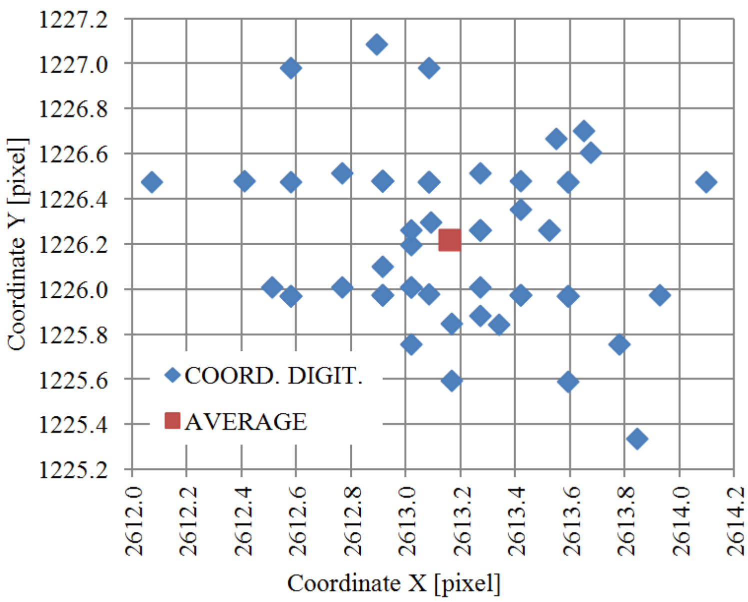

Figure 4.1. CP's digitalizing accuracy test

The standard deviation found by independently repeating coordinate digitalization of the same points was about 0.5 pixels (fig. 4.1).

Accuracy assessment

This choice allowed to address inexperienced users by setting up a simplified, mostly automated photogrammetric workflow able to define external and internal parameters for image orientation, and to generate a dense 3D cloud, used to derive mesh models of the survey object.

All processing, except when explicitly stated, was performed according to this mode, i.e. the most likely used by operators without field-specific training: calibration parameters of camera and lens are computed, taking into account operating conditions, during self-calibrating bundle adjustment procedure.

The same UAV-borne image set has yielded, in different modes, models of the façade and the roof, which, upon being framed in the same reference system, have been integrated with the TLS models (fig. 4.2).

Figure 4.2. Laser scanner - UAV SfM-MVS integrated model

Photogrammetric processing was performed according to Constrained and FreeNet configurations for bundle adjustment. Each configuration was processed considering different layouts and number of Ground Control Points (GCPs).

The same set of UAV-based images has yielded façade and roof models in different modes. Accuracy of photogrammetric output was evaluated by means of the Root Mean Square Error (RMSE) estimator and was computed by comparing coordinates of CPs measured on 3D models against reference coordinates.

Accuracy assessment of the photogrammetric models of the façade

Upon processing UAV-borne images of the façade, two models were generated with different GCP layouts (fig. 4.3):

- Case A: 6 GCPs evenly distributed on the façade;

- Case B: 12 GCPs evenly distributed on the façade.

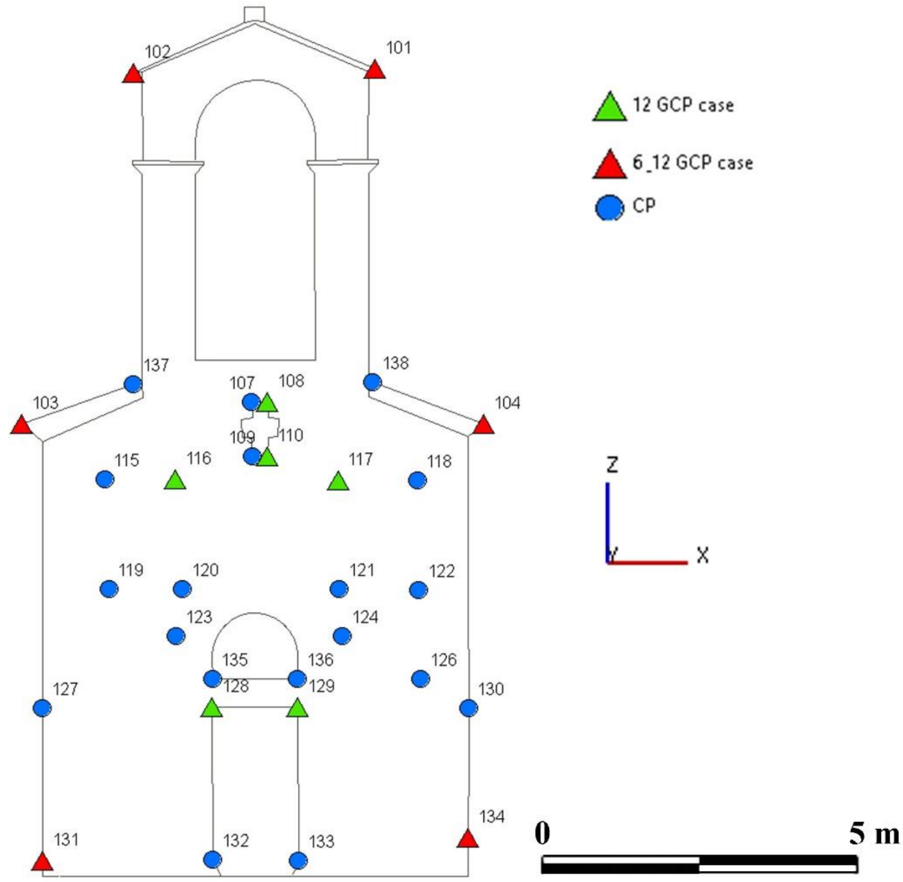

Figure 4.3. Façade GCPs and CPs map.

In order to evaluate the influence of number and layout of GCPs on model accuracy, both topographic and laser scanning surveys were assumed as reference.

As regards the check against the topographic survey, model deviations were measured at 19 Check Points (CPs). Tables 4.1 and 4.2 summarize the results.

n. of GCPs	Case	n. of CPs	RMSE Y axis (m)	RMSE X axis (m)	RMSE Z axis (m)	RMSE XZ plane (m)
6	A	19	0.011	0.006	0.008	0.010
12	B	19	0.009	0.005	0.008	0.009

Table 4.1. RMSE in FreeNet Solution Type

n. of GCPs	Case	n. of CPs	RMSE Y axis (m)	RMSE X axis (m)	RMSE Z axis (m)	RMSE XZ plane (m)
6	A	19	0.005	0.008	0.006	0.010
12	B	19	0.006	0.004	0.006	0.007

Table 4.2. RMSE in Constrained Solution Type

Analysis of the results shows that RMSE values are virtually constant throughout the variation of GCP number, for both FreeNet and Constrained processes, ranging from 3 to 5 GSDs and from 2 to 4 GSDs respectively.

It can be assumed that a portion of these errors depends on collimation errors on check points identified without dedicated targets (standard deviation evaluated in 0.5 pixels).

Overall, Constrained processing improves RMSE by a 1.5-2 factor along the Y-axis, that is, in this case, the depth of the object.

It can be concluded that this particular case of virtually planar surface does not yield deviations of any significance depending on GCP number and processing mode.

Self- calibration results of bundle adjustment of the façade

For each processing mode, the computed calibration parameters were compared. In the PhotoScan environment, this kind of analysis solved some issues due to the unavailability of statistical parameters of computed values.

Calibration results (Table 4.3) show that internal camera parameters vary depending on the processing mode. The internal camera parameters as computed via calibration, especially referring to FreeNet processing, differ from those stated by the manufacturer.

Calibration parameters	FreeNet	Constrained 6 GCPs	Constrained 12 GCPs
width	6016	6016	6016
heigh	4016	4016	4016
fx	8131.396	8208.954	8214.459
fy	8125.933	8199.890	8205.916
cx	2894.511	2923.836	2926.630
cy	2043.073	2012.728	2011.585
skew	31.634	23.810	23.065
K1	-9.61E-02	-9.34E-02	-9.29E-02
K2	-8.79E-02	-9.50E-02	-9.52E-02
K3	6.86E-01	7.13E-01	7.12E-01

Table 4.3. Camera calibration parameters calculated by Photoscan (pixel unit)

Since pixels, as used in Table 4.3, do not allow for effective metric comparison of the results, camera calibration parameters were exported in the Photomodeler format, which allows generation of metric results. Results of this operation are reported in Table 4.4

Calibration parameters	FreeNet	Constrained 6 GCPs	Constrained 12 GCPs
f	49.986	49.990	49.991
Xp	17.798	17.809	17.814
Yp	12.570	12.272	12.256
Fw	36.992	36.642	36.618
Fh	24.711	24.488	24.470
K1	3.44E-05	3.42E-05	3.41E-05
K2	3.77E-08	3.63E-08	3.57E-08
K3	-7.31E-11	-7.30E-11	-7.22E-11

Table 4.4. Camera calibration parameters calculated by Photoscan in Photomodeler format (mm unit)

Focal length is constant and coordinates of the principal point show a variation in the sub-millimetre range (Table 4.4) for the Y coordinate computed in FreeNet, compared to values computed in Constrained mode.

Radial distortion parameters (k1, k2, k3) are in the same range, and of concordant sign for each processing mode.

Tangential distortion parameters were not included in the tables because their influence is at least a magnitude order smaller than radial distortion (according with Remondino & Fraser, 2006).

Accuracy assessment of photogrammetric models of the roof

Accuracy of UAV-based models of the roof was checked against the topographic survey.

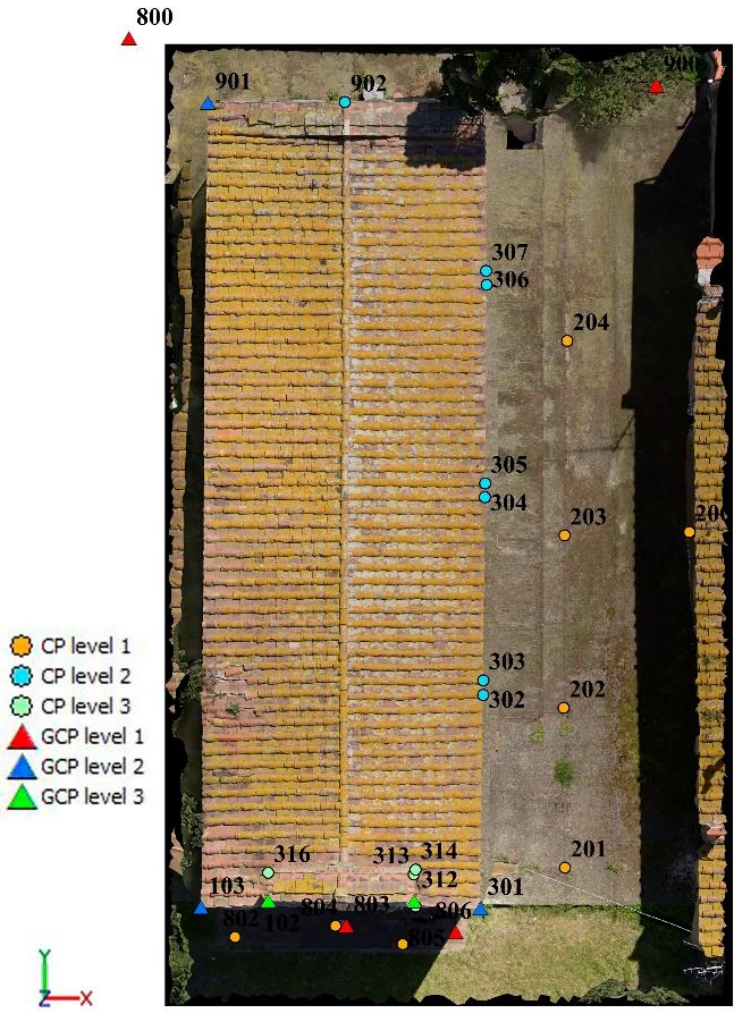

Figure 4.4. Roof GCPs and CPs map.

For this purpose, the following GCP layouts were considered (fig. 4.4):

- Case A: 4 GCPs on the ground;

- Case B: 4 GCPs on the ground and 3 GCPs along the eaves;

- Case C: 4 GCPs on the ground, 3 GCPs along the eaves and 2 GCPs on top of the belfry.

The remaining 20 points were used as an independent set against which model deviations were measured (CPs). Tables 4.5 and 4.6 summarize results of this global comparison as RMSE.

n. of GCPs	Case	n. of CPs	RMSE Z (m)	RMSE X (m)	RMSE Y (m)	RMSE XY (m)
4	A	20	0.033	0.019	0.016	0.025
4+3	B	20	0.030	0.010	0.007	0.012
4+3+2	C	20	0.030	0.010	0.007	0.012

Table 4.5. RMSE in FreeNet Solution Type

n. of GCPs	Case	n. of CPs	RMSE Z (m)	RMSE X (m)	RMSE Y (m)	RMSE XY (m)
4	A	20	0.048	0.013	0.004	0.013
4+3	B	20	0.029	0.008	0.004	0.009
4+3+2	C	20	0.030	0.007	0.005	0.009

Table 4.6. RMSE in Constrained Solution Type

As regards FreeNet processing, higher numbers of evenly distributed GCPs, not only at ground level but also on the roof, led to an improvement in RMSE values, particularly for the X and Y components. Adding 2 more GCPs on top of the bell tower (Case C) did not entail any difference.

As regards Constrained processing, GCP layout as described in case B significantly cut down the RMSE of the Z coordinate. In this case, too, case C layout did not change RMSE values compared to case B.

Comparison of Free Net and Constrained processing showed that:

- For case A, Constrained solution had a higher Z RMSE than Free Net, while it was substantially lower for X and Y. This behaviour may be referred to bad conditioning of bundle adjustment along the Z-axis, while planimetrically the constraints assigned to GCPs had a definite positive action.

- For case B, RMSE value for Z was virtually the same in both modes, while it decreased for X and Y in Constrained processing.

- Case C did not show any difference compared to case B.

Addition of the two constraint points on the bell tower did not yield any significant improvement in RMSE, especially for the Z direction, possibly because the tower, due to its small footprint and different morphology compared to the remaining portion of the roof, has a marginal importance in the bundle adjustment global processing.

These data point out that any increase in the number of GCPs positively affects RMSE only if they are evenly laid out across the survey object, otherwise their action seems negligible.

Tables 4.7 and 4.8 show the local variations of CP accuracy depending on processing mode, number and different level distribution of GCPs.

Ground CPs (level 1) had virtually identical RMSE for X and Y, independently from GCP number and layout, for both FreeNet and Constrained processing. As for Z coordinates, case A (only ground-level GCPs) in Constrained processing yielded the poorer performance.

As regards roof-level CPs (level 2), elevation accuracy for case A was better with Free Net processing; case B improved CP RMSE over case A, especially for the Z component, while case C did not yield any improvement over case B.

CPs height distribution (level)	Case	RMSE Z axis (m)	RMSE X axis (m)	RMSE Y axis (m)	RMSE XY plane (m)
8 CPs on the ground (level 1)	A	0.046	0.017	0.002	0.017
	B	0.042	0.015	0.004	0.016
	C	0.042	0.015	0.004	0.016

8 CPs on the roof border (level 2)	A	0.030	0.014	0.018	0.023
	B	0.026	0.002	0.007	0.007
	C	0.026	0.002	0.007	0.007

4 CPs on the top of bell tower (level 3)	A	0.015	0.032	0.038	0.049
	B	0.015	0.015	0.012	0.016
	C	0.015	0.015	0.012	0.016

Table 4.7. RMSE in FreeNet Solution Type

CPs height distribution (level)	Case	RMSE Z axis (m)	RMSE X axis (m)	RMSE Y axis (m)	RMSE XY plane (m)
8 CPs on the ground (level 1)	A	0.056	0.015	0.002	0.015
	B	0.046	0.013	0.003	0.013
	C	0.047	0.013	0.003	0.013

8 CPs on the roof border (level 2)	A	0.042	0.010	0.002	0.011
	B	0.018	0.003	0.002	0.004
	C	0.019	0.003	0.005	0.005

4 CPs on the top of bell tower (level 3)	A	0.043	0.013	0.010	0.016
	B	0.019	0.007	0.009	0.011
	C	0.018	0.004	0.010	0.010

Table 4.8. RMSE in Constrained Solution Type

Results of self-calibration for bundle adjustment on the roof

Camera calibration parameters, computed in the different processing modes, were also analysed for the roof (tables 4.9 and 4.10).

Calib. param.	Free Net	Constrain. Case A	Constrain. Case B	Constrain. Case C
width	6016	6016	6016	6016
heigh	4016	4016	4016	4016
fx	8680.630	8635.889	8626.328	8623.675
fy	8680.630	8632.405	8622.754	8620.119
cx	3005.679	2995.339	2995.072	2994.953
cy	1979.953	1972.135	1970.520	1970.326
skew	0.000	6.032	6.105	6.103
K1	-1.09E-01	-1.06E-01	-1.06E-01	-1.06E-01
K2	7.38E-02	-5.65E-02	-6.13E-02	-6.15E-02
K3	2.33E-01	9.89E-01	1.01E+00	1.01E+00

Table 4.9. Camera calibration parameters calculated by Photoscan

Calib. param.	Free Net	Constrain. Case A	Constrain. Case B	Constrain. Case C
f (mm)	50.000	49.999	49.999	49.999
Xp	17.313	17.343	17.360	17.365
Yp	11.404	11.423	11.426	11.429
Fw	34.652	34.831	34.870	34.881
Fh	23.132	23.261	23.287	23.294

K1	4.34E-05	4.18E-05	4.15E-05	4.16E-05
K2	-4.83E-09	2.12E-08	2.20E-08	2.21E-08
K3	-2.30E-11	-8.24E-11	-8.39E-11	-8.38E-11

Table 4.10. Camera calibration parameters calculated by Photoscan in Photomodeler format (mm unit)

Conclusions

The accuracy tests were conducted on an object of comparatively small dimensions with a regular, roughly parallelepiped shape, save for the bell tower, which is different in size, shape and position.

The tests reported that higher numbers of GCPs, evenly distributed both along and orthogonally to the photographic axis, increase model accuracy; besides, this was true particularly when surveying objects effectively spread in three dimension, while no substantial improvements in accuracy were detected in planar elements, such as façades.

As for the bell tower, it is apparent that the use of GCPs placed at its top did not entail a significant accuracy improvement of the different models. This could be due to several factors, such as the lower number of GCPs placed at this level and their reduced influence in the calculation algorithm compared to GCPs distributed evenly on the surfaces of greater extension.

While identification of GCPs and CPs by means of available details, rather than with ad hoc targets, denotes a speed survey and saves costly operations, on the other hand is more prone to errors related to a difficult and less accurate collimation on the images.

4.1.4.2. Harzburger Hof hotel

As previously pointed out, this survey was carried out in an emergency situation (Martínez-Espejo Zaragoza, et al., 2017), where logistics and safety issues required application of surveying methodologies beyond best accuracy boundaries in order to obtain a geometrical model of the disaster scene as comprehensive as possible.

Comparison of TLS and UAV- based photogrammetry models

Firstly, it must be noted that the photogrammetric surveys can be carried out assuming as tie points and GCPs only points surveyed by total station and marked with specific targets. In the present case, where logistics issues overcame rigorous planning as to GCP number and layout, two separate photogrammetric models were processed: one (SfM_A) obtained with topographically measured tie points only (15 points), and the other (SfM_B) where some accessory tie points (35 points) were added on the images so to have an even layout and at least three points could be collimated on each image.

GCPs provided a common reference system, used for framing of laser scans and scaled rototranslations of the photogrammetric model obtained by Photoscan.

As previously stated, the disaster area presented accessibility issues that prevented its complete survey using only total stations; besides, buildings and vegetation affected the GNSS survey, with accuracy values ranging from typical RTK (2 ÷ 3 cm) to up to 3x greater.

Results

A check between TLS point clouds T1 and T2 and photogrammetric point cloud SfM_A yielded a mean difference of about 10cm, with standard deviation of about 1 ÷ 2cm on the ground, and a mean difference of about 3 ÷ 4cm with standard deviation of about 2cm on the roofs (tables 4.11 and 4.12).

GROUND			
reference	compared	mean [m]	standard deviation [m]
L1_TR	SFM_A_TR	0.117	0.014
L2_TR	SFM_A_TR	0.112	0.027

Table 4.11. Comparison of TR between TLS and SfM_A clouds

ROOFS			
reference	compared	mean [m]	standard deviation [m]
L2_T1	SFM_A_T1	0.032	0.020
L1_T2	SFM_A_T2	0.040	0.023
L1_T3	SFM_A_T3	0.030	0.028

Table 4.12. Comparison of Tn between TLS and SfM_A clouds

Checking the same TLS clouds against photogrammetric cloud SfM_B yielded comparable standard deviation (σ) values, with a substantial improvement in the mean difference (tables 4.13 and 4.14).

GROUND			
reference	compared	mean [m]	standard deviation [m]
L1_TR	SFM_B_TR	0.020	0.019
L2_TR	SFM_B_TR	0.018	0.028

Table 4.13. Comparison of TR between TLS and SfM_B clouds

ROOFS			
reference	compared	mean [m]	standard deviation [m]
L2_T1	SFM_B_T1	0.012	0.012
L1_T2	SFM_B_T2	0.019	0.022
L1_T3	SFM_B_T3	0.017	0.019

Table 4.14. Comparison of T*n* between TLS and SfM_B clouds

Conclusions

As clearly shown by the results, higher number and better layout of the tie points entail better modelling. This should be considered when planning the tie points layout. The amount and distribution of tie points greatly influences the accuracy and precision of the survey.

4.1.5. Bibliography

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4.2 BEST METHODS FOR SURVEY ASSESSMENT

4.2.1 Considerations about the quality of a photogrammetric restitution project

In photogrammetry, as claimed by Manferdini & Remondino (2010: 162-199), accuracy of measures and three-dimensional restitution depends on captured data quality, but also on software versatility and operator skills.

Accuracy of the capture net increases with the B/D ratio and when more converging-axis images are used than parallel-axis images. This is because the base-depth relation in images influences the obtainable accuracy of depth estimation of the objects in the scene, and use of convergent images allows in many cases to eliminate shaded areas due to acute angles, many moulded details, etc.

3D reconstruction accuracy improves significantly with the increase of the image number in which any point is detectable; however, improvements are less significant beyond a certain increase. Manferdini & Remondino (2010: 162-199), in their tests, generated several models of the same object. While use of multiple images yielded detailed models, results showed that when fewer pictures were used, whereas at first addition of an image did increase the detail level of the model, this did not improve appreciably upon including more than six images covering the same part.

3D reconstruction accuracy also increases if the geometry configuration is suitable and the measured points are easily detectable (as targets) and well distributed across the image. It is important to distribute points throughout the image in a more or less uniform way, for rather greater precision can occur in the most populated parts of points and higher deviations between images in areas lacking homologous points. Moreover, 3D point accuracy is linked to collimation accuracy on the image, which mainly depends on operator skill and use of targets.

Despite fulfilling all these premises that on the other hand, in many cases, these are not possible by the specific situation of the case study, once the restitution is made the results must also be analysed. If more than one technique is used, not just the photogrammetric, or several types of sensor, should also be considered if the results are compatible in terms of accuracy and detail level.

4.2.2. Methodology for data comparison

In order to attain satisfactory results, field operations of a survey require greatest attention at every stage. However, once these are completed and the final model is obtained, some checks need to be performed in order to confirm that this is consistent with respect to the sought results.

In theory, the most straightforward way to perform a comparison would be virtual model against actual object. However, in practice this can be more complicated, perhaps, than the survey work itself, since it requires accurate measurements in both. In this case, a number of parameters must be taken into account for their influences on measurements. For the actual object these include measuring instruments, methods, and so on, while for the virtual models the measuring software, measuring procedures, and so on. Another approach uses Control Points (CP), while the last one performs checks between virtual models, each carrying an exact definition of its accuracy.

Thus, the possible ways to carry out this comparison are:

1. Actual object - Virtual model
2. Virtual model - CP
3. Virtual model - Virtual model

Rather than introducing new methods or improving existing ones, the following investigation of the possible methods of comparison aims at the proposal of a methodology including each one of the 4 points described in the thesis so to obtain a well-structured complete process. It is important to consider each aspect individually even if it is ultimately part of a whole.

4.2.2.1. Actual object - Virtual model

As mentioned in the previous paragraph, the simplest way to check a survey is the comparison between the virtual model and the actual object. This can be carried out by making three-dimensional measurements in the software and directly on the object. In this case understanding the accuracy of the measuring tools in the software and in the real object is very important, as they affect the tolerance of these measurements.

The Palazzo Roncioni case study provided an example of comparison between actual object and virtual object, by printing areas of the unwrapped virtual vault on A0 translucent paper, as will be explained later in the case studies section (4.2.3).

In the archeological field, another solution would be to take profiles with a profile gauge and compare these with sections performed in the three-dimensional virtual model (Martínez-Espejo Zaragoza, 2010).

4.2.2.2. Virtual model - CP

The most common comparison is based on Control Points (CP). Section 4.1 included a description of Ground Control Points (GCP) as points that allow to scale the virtual model and to georeference it in a specific reference system, and of CPs as points that allow the accuracy control of the model. CPs would be used to perform the comparison by specific measures, and are generally captured by a total station or laser scanner and have well-defined accuracy coordinates. As these points are not involved in the image orientation calculating process, they are not influenced by the correction of least squares to reduce the error between these points by adjusting the model. Thus, the unaffected points in the model allow to calculate the deviation from the original. In this case, the accuracy depends exclusively on operator skills as to measuring stations and collimating these points in the images.

4.2.2.3. Virtual model – Virtual model

Punctual results may not always provide a global perspective on the *status quo*; on the other hand, when comparing surveys of the same object performed at different times it is important to highlight any modifications on the whole object, rather than only specific points. Likewise, different survey methodologies can have different precision or detail levels, or only one of them has a given verifiable accuracy. In all these cases, the comparison is no longer made between virtual model and actual object, but between two different virtual models.

As already stated in literature (Martínez-Espejo Zaragoza, et al., 2017), the most frequently used methodologies for comparing 3D point clouds are (Lane, et al., 2003):

a. DEM of Difference (DoD)
b. Direct Cloud-to-Cloud (C2C)
c. Cloud-to-Mesh distance or Cloud-to-Model distance (C2M)
d. Multiscale Model to Model Cloud Comparison (M3C2)

Following are the relevant details about each of these methodologies:

a. DEM of Difference (DoD). It is most commonly used for objects close to horizontal planes. Each of the point clouds is firstly framed in a regular grid (Digital Elevation Model - DEM); subsequently, a DEM of the differences is produced, by a pixel-per-pixel comparison of the DEMs previously created. This comparison methodology does not perform well with objects mainly developing along vertical planes or featuring highly sloping surfaces.

b. Direct Cloud-to-Cloud (C2C). This is a direct 3D comparison of the point clouds, without any need to create regular grids or meshes of the original data, or to compute the normal to the surfaces. For each point in the checked cloud this technique seeks the nearest point in the reference cloud, defining the distance based on different performing algorithms (Tsakiri & Anagnostopoulos, 2015), as listed below:

- Nearest neighbour
- Nearest neighbour with local modelling
- Normal shooting
- Iterative Closest Point (ICP)

The simplest approach to cloud comparison is the Nearest Neighbour Search (NNS), which computes the Euclidean distance between closest points. Although this calculation does not provide hypotheses, its results can be unreliable due to (image) roughness and different point density between clouds.

The Nearest Neighbour with local modelling algorithm is a variant of the above, which calculates point distances from a local surface, obtained by a set of points in the proximity. This methodology is less sensitive to point density differences, but can sometimes yield unexpected results, due to the limited amount of points, which the modelling is based on (corners and close curvature surfaces). Modelling can use several mathematical surfaces.

The Normal shooting algorithm calculates the Euclidean distance between two points, where the point in the reference cloud has the smallest distance from the normal vector to the point on the compared cloud.

The ICP algorithm searches for the smallest distance between clouds by splitting the global cloud in to smaller ones. It is most used for point cloud registration. It is less sensitive to local noise, although it may not be fit for shift evaluation between clouds representing very wide areas.

c. Cloud-to-mesh distance or cloud-to-model distance (C2M). It creates mesh or triangulated models of the reference point cloud, which are used to measure orthogonal distances for each point in the compared cloud (Cignoni & Rocchini, 1998, see also Monserrat & Crosetto, 2008 and Olsen, et al., 2010 for recent reviews). This procedure is most suited to sub-planar objects, due to a tendency to smooth out details with possible relevance in local properties evaluation.

d. Multiscale Model to Model Cloud Comparison (M3C2). It works directly on raw point clouds, with no meshing or gridding, and is split in two main steps:

- *Estimation of surface normal orientation at a scale consistent with local surface roughness.*

- *Quantification of the mean cloud-to-cloud distance (i.e. surface change) along the normal direction (or orthogonal vector), which includes an explicit calculation of the local confidence interval. A point-specific normal vector is calculated by fitting a plane to neighbouring 3-D points that are contained within a user-specified search radius. To avoid the fluctuation of normal vector orientations and a potential overestimation of the distance between two point clouds, the radius, or scale, used for normal calculation needs to be larger than the topographic roughness, which is calculated as the standard deviation of local surface elevations. The orientation of the surface normal around a point is therefore dependent on the scale at which it is computed* (Lague, et al., 2013).

4.2.3. Case studies

From these data comparison typologies, some case studies implementing these accuracy checks were selected.

The first case study was carried out only with ground-based techniques, and is the only case in which accessibility and security features allowed to test the virtual-actual comparison, not only with punctual elements but also with partially meshed zones. In this case, it was necessary to perform enough tests to analyse the Image matching techniques as much as possible, so to be able to concentrate in subsequent cases on UAV surveys, thus introducing other factors that were not dealt with this first case.

4.2.3.1. Palazzo Roncioni Vault (Pisa)

This case study, as already stated, was presented in these articles: Martínez-Espejo Zaragoza, et al., 2014, Caroti, et al., 2015A and Bevilacqua, et al., 2016. Although several aspects were discussed on each occasion, the present work focuses on the part that regards accuracy checking and comparison of virtual model – actual object, virtual model - CP and virtual model - virtual model.

Furthermore, one of the issues addressed in Bevilacqua, et al., 2016 is of special interest, i.e. the vault development, which enables true-scale 2D restitution. The goal of this research was to study a simplified methodology enabling both planar development ("unwrapping") of geometry and texture of frescoed vaults (surveyed with geomatics techniques) and checking of the errors related to the different operating steps. Its interest is based on the fact that unwrapping enable a comparison between actual object and virtual model.

The frescoed vault models that are developed are two: the mesh obtained from laser scanning only and the merger of the laser scanning mesh with texture projected from Image-based Modelling.

As the integration topic will be discussed in the next section, in this section there is only a need to point out that partial results of SfM-MVS modeling were used, i.e. the camera orientation parameters, and images were projected on the most faithful TLS model. Prior to the projection, TLS and SfM/MVS models were compared; the TLS model was subsequently imported into SfM-MVS software and had the photo-realistic texture applied (fig. 4.5).

Figure 4.5: Laser scanner model textured via SfM-MVS software.

Results

Several results were checked for both geometric precision of the different models obtained and precision of placement, dimension and shape of the applied textures. Finally, the quality of the planar development of the vault wass assessed.

Geometrical comparison between TLS and SfM/MSV models

In one of the articles quoted above (Martínez-Espejo Zaragoza, et al., 2014) the complete models were compared. Figure 4.6 shows the comparison between the two mesh models, one taken as a reference, obtained from processing of the TLS survey (Laser Model), and the other resulting from SfM-MVS software (SfM/MVS Model).

The latter well represents the vault in its entirety (standard deviation equal to less than 3mm) but, being strongly dependent on the pattern present on the vault, is not able to ensure a homogeneous local precision in rendering small morphological variations. Greater deviations (ranging in absolute value between 7 and 10 mm), coincident with cracks or margins of plaster collapse and gaps in the fresco, are quite obvious. Full knowledge of these geometries is important for restoration planning or safety implementation works.

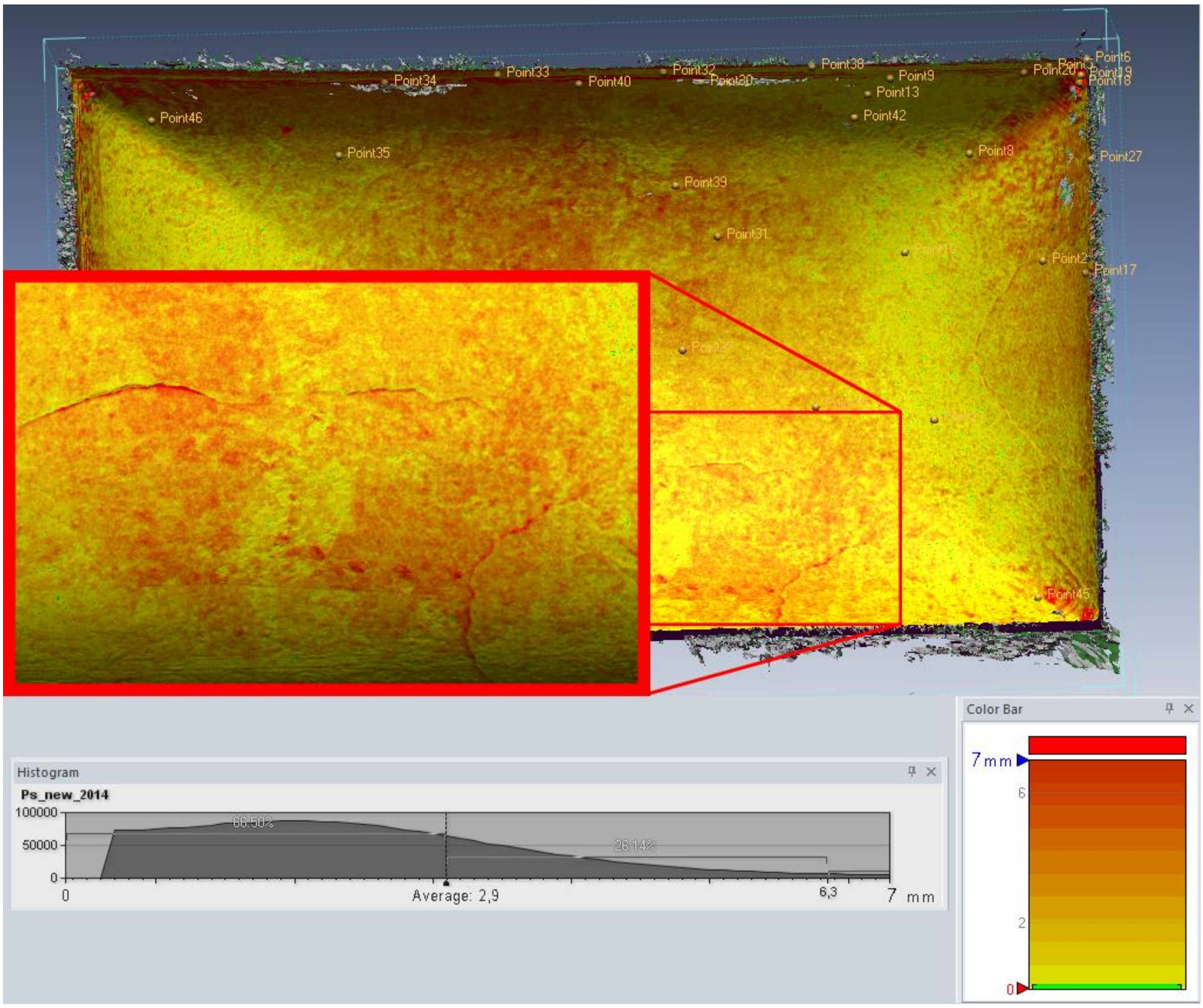

Figure 4.6. Distance in absolute values between mesh models obtained from laser scanning survey and from SfM-MVS software.

It is noted that the calculation of the exterior orientation of the cameras performed through SfM-MVS software is substantially correct, as shown by the value of the mean reprojection error equal to 0.70 pixels on an average of 9000 tie points for each photogram.

It should also be noted that operator input in this procedure is limited to the insertion of the Control Points (10 points input for the test) that allow scaling and georeferencing of the model in the same reference system TLS. It should be emphasized that the process of creating the model using SfM-MVS software and then calculating the orientation parameters of the cameras has required one working day for one person.

As reported in Bevilacqua, et al., 2016, the comparison was extended. Thus, on one side, more complete models were compared, not only mesh but also point cloud, and, on the other hand, some of the most important parts of the vault were selected for investigation.

The laser scanning coloured point cloud model (Cloud LASER) was assumed as the absolute geometric reference in this application. It features very high point density, and allows extraction of coordinates of features for both geometry (cracks, gaps, etc.) and image (boundary lines, colour transitions, etc.) with a sub-centimetre resolution.

Standard deviation obtained by comparing Cloud LASER with Model LASER is 1 mm, with peaks in the 3 mm range. These results highlight that the transition from point cloud to surface model entails a small decay of geometric precision.

A second check was performed comparing Cloud LASER with Cloud SfM/MVS; the standard deviation averaged at 3 mm, with peaks of about 6 mm.

Finally, Cloud LASER was compared against Model SfM/MVS; the standard deviation was 3 mm on average, peaking at about 10mm.

Maximum deviation values are in the range of 7-10mm and refer to cracks and plaster collapse borders. Figures 4.7–4.11 show an overview of the fresco and some details on local deviations.

Taking into account all these cases, greater deviations are found when surveyed surfaces are orthogonal to the vault. SfM/MVS methodology does not correctly represent the transitions typical of deep cracks and delamination. This result is in the candidate’s opinion due to the fact that these surface regions are acquired by inclined views with different inclinations and sometimes with the camera axis parallel to the surface. This fact, reported in the literature, leads to worse performance of the matching algorithms (Remondino, et al., 2014).

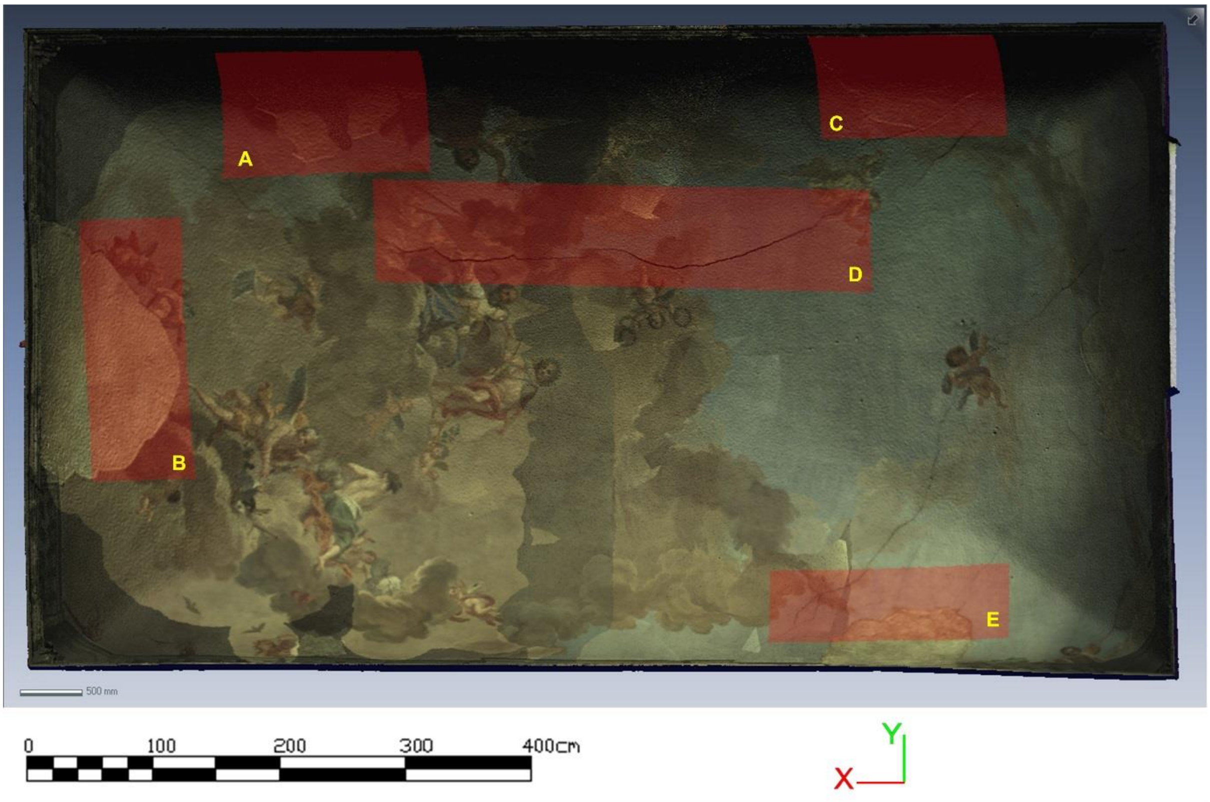

Figure 4.7. Regions checked for deviations between cloud LASER and model SfM/MVS.

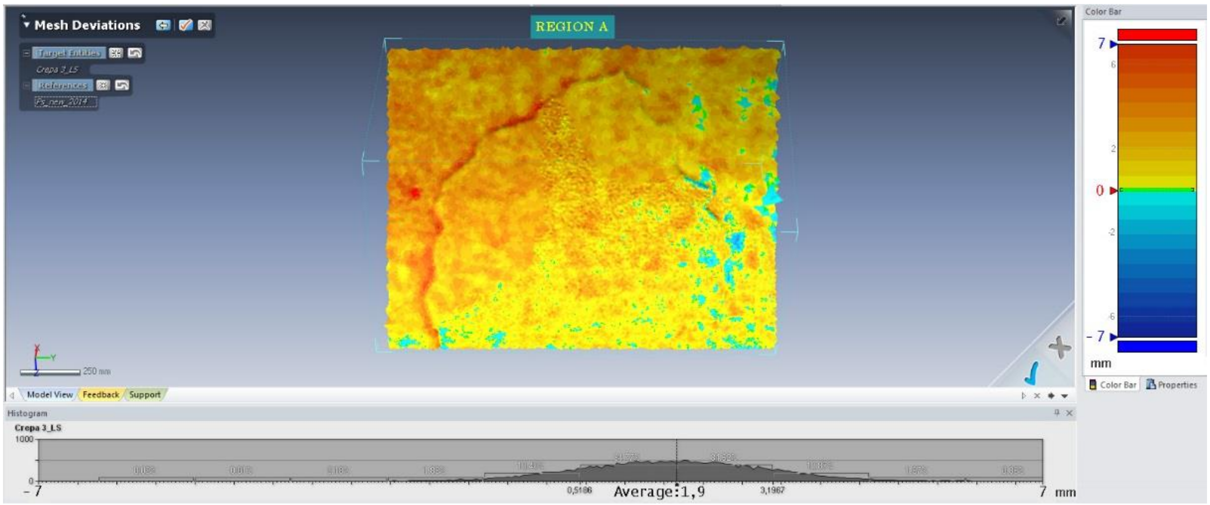

Figure 4.8. Region A: total plaster collapse borders.

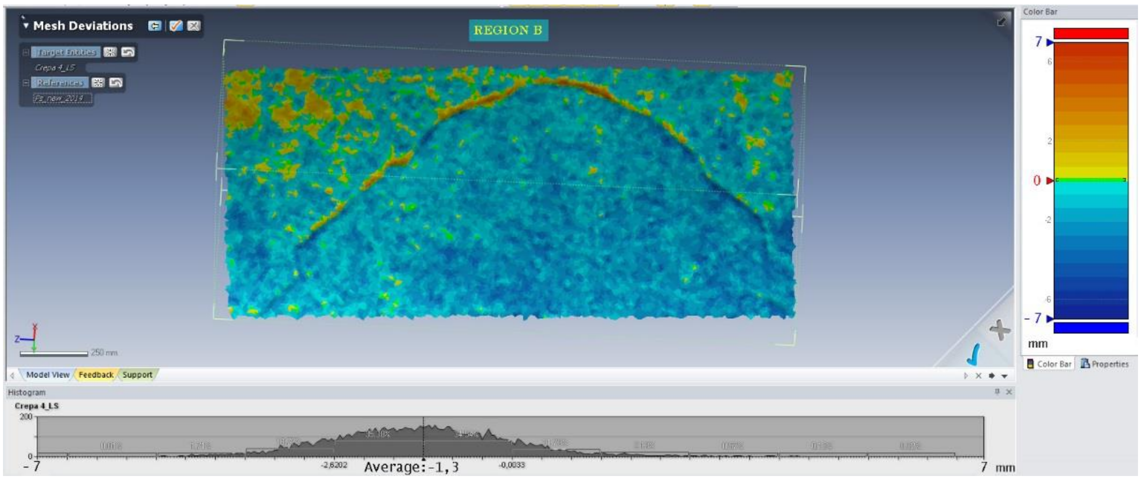

Figure 4.9. Region B: total plaster collapse borders.

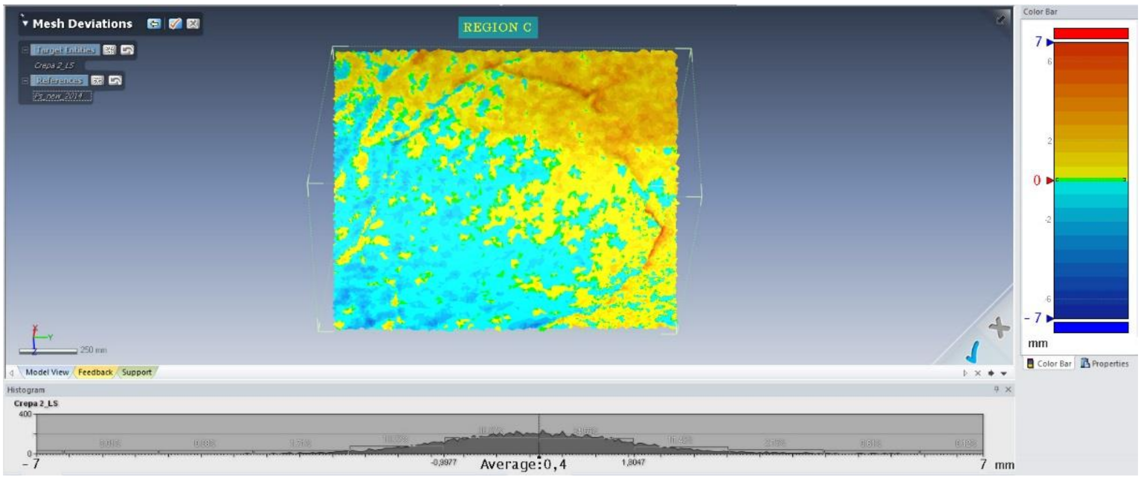

Figure 4.10. Region C: gap in the fresco.

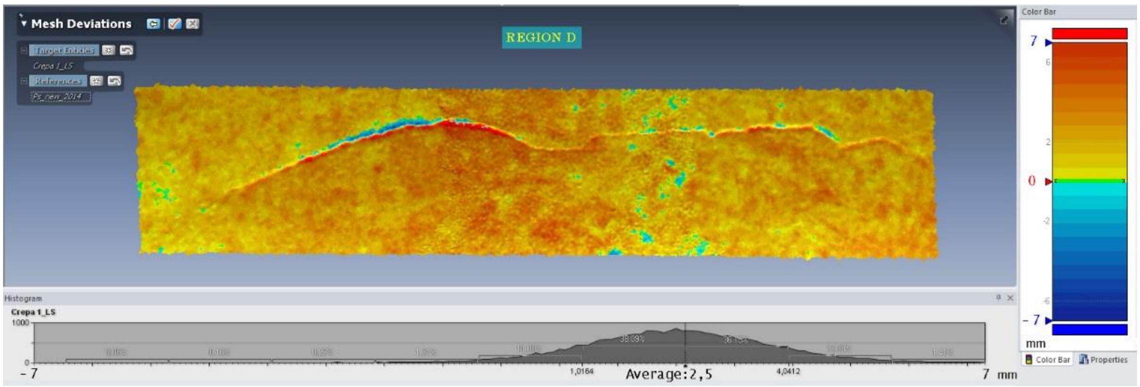

Figure 4.11. Region D: crack in the topmost region of the vault.

Hence, the overall accuracy of the SfM-derived model is good (3 mm), but shows some flaws precisely in the regions of most interest to restorers.

Texture dimension and positioning accuracy assessment

After geometric accuracy of the models was checked, texturing precision was also monitored. For this purpose, the coordinates of 36 Control Points (CPs) were extracted by Cloud LASER. These coordinates were firstly compared with those obtained by digitizing the points on the images and obtaining their 3D position in Cloud SfM/MVS (fig. 4.12). The comparison provided the statistics displayed in Table 4.15.

Table 4.15. CP coordinates comparison Cloud LASER—Cloud SfM/MVS.

	X	Y	Z
mean (m)	0.000	0.000	0.000
max (m)	0.005	0.005	0.010
STDV (m)	0.002	0.003	0.004

Note: The values are in line with the geometric comparison between point clouds LASER and SfM/MVS.

Subsequently, the same points were digitized directly on Model SfM/LASER. A comparison with the reference CP coordinates yielded the results displayed in Table 4.16.

Table 4.16**.** CP coordinates comparison Cloud LASER—Model SfM/LASER.

	X	Y	Z
mean (m)	0.000	0.000	0.000
max (m)	0.019	0.023	0.026
STDV (m)	0.007	0.007	0.008

This comparison shows that precision checks on texture yielded slightly worse results relative to those on geometry. Such an outcome was predictable, assuming the addition of errors for geometry with those for image orientation and texture projection, as well as those for direct CP collimation on Model SfM/LASER.

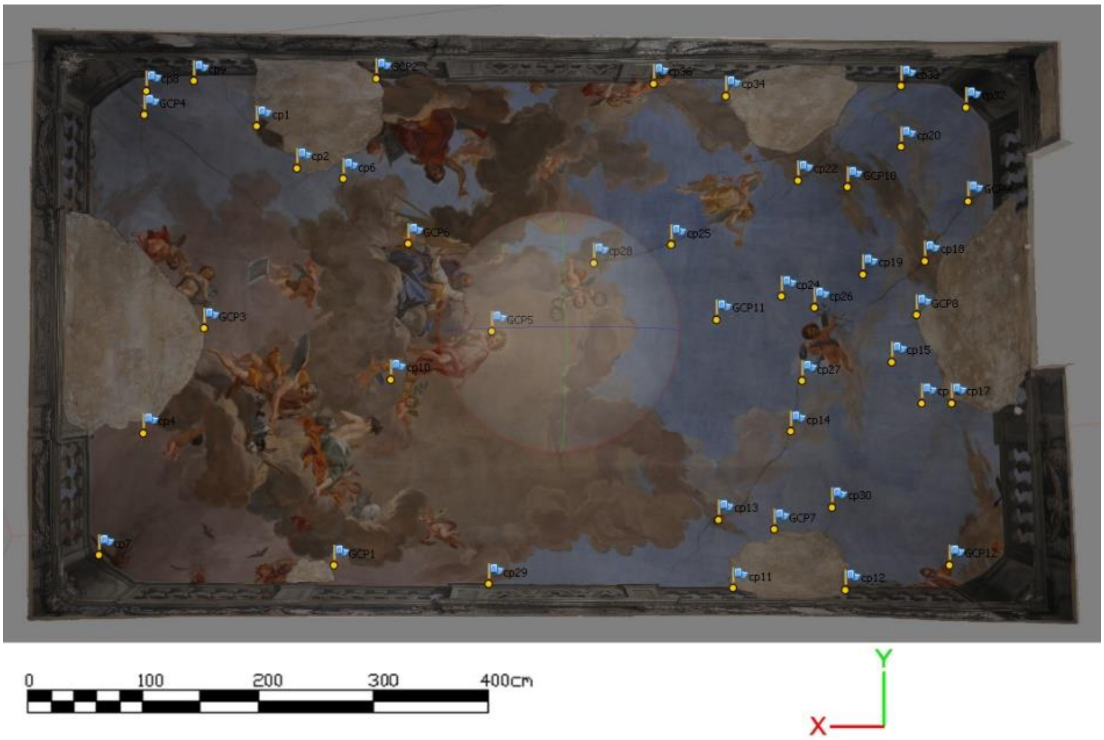

Figure 4.12. CPs on the vault.

Vault Development

The specific methodology used in vault development is detailed in section 4.4.2. Wrap to frescoed vaults, which explains in detail all the steps necessary to perform the unwrap with manual methods, from two models, one based exclusively on the textured TLS model and another laser-based model with image-derived texture. While more specific topics of descriptive geometry are analysed, the interesting part in this section is the direct comparison against the actual vault.

In this study, besides the 3D comparison between Model SfM/LASER and Cloud LASER, planar development was also validated at actual scale. Some portions of the image, representing the vault development, were printed at 1:1 scale on A0 tracing paper. Subsequently, restorers checked the prints directly with the represented fresco portions (fig. 4.13), noticing the accordance of shapes and dimension of the checked portions in line with the deformations already expected and accepted in the processing steps. On the same tracing paper sheet, restorers had drafted the outlines of the actual fresco paintings; the resulting accuracy was 3 millimetres.

Figure 4.13. Development accuracy assessment at 1:1 scale.

The methodology proposed for modeling, texturing and planar development was verified by both calculating the theoretical error introduced by the single processing step and comparing the final products with a reference survey and then directly with the survey object.

The theoretical development accuracy is 3 mm. The comparison between the laser scanning model textured with oriented images through SfM-MVS and the original laser scanning point cloud yielded a 3-mm accuracy. Finally, the direct verification of the development of the model confirmed an accuracy of 3 mm, which allowed to obtain drafts that are fully usable by restorers for 3D fresco reconstruction on a vaulted surface.

4.2.3.2. San Miniato Church (Cascina, Pisa)

The second case study, as already stated, was presented in two articles (Martínez-Espejo Zaragoza, et al., 2015; Caroti, et al., 2015B). As both articles covered several topics the present paper will focus on accuracy checks and comparison of virtual models.

In this case, comparisons between virtual models (laser and photogrammetry) and between virtual models (photogrammetry) and CPs were performed. In the first kind of comparison models obtained by photogrammetry were compared against the reference TLS model, considering the different GCP settings. In the second, control points were used to compare the attainable accuracy levels based on GCP position and eventual role in the calculation of internal camera parameters.

Results

Different tests were performed for both façade and roof, as already seen in 3.1.4.1.

In the façade case, it was possible to make two different comparisons, with CPs (analysed previously) and between virtual models. In the virtual comparison (fig. 4.14), SfM/MVS-derived models were compared with TLS models, allowing to analyse accuracy homogeneity of the models on the entire surface. The average deviations of the models in the different processing modes ranged between 6mm and 11mm, with higher values restricted to some spots.

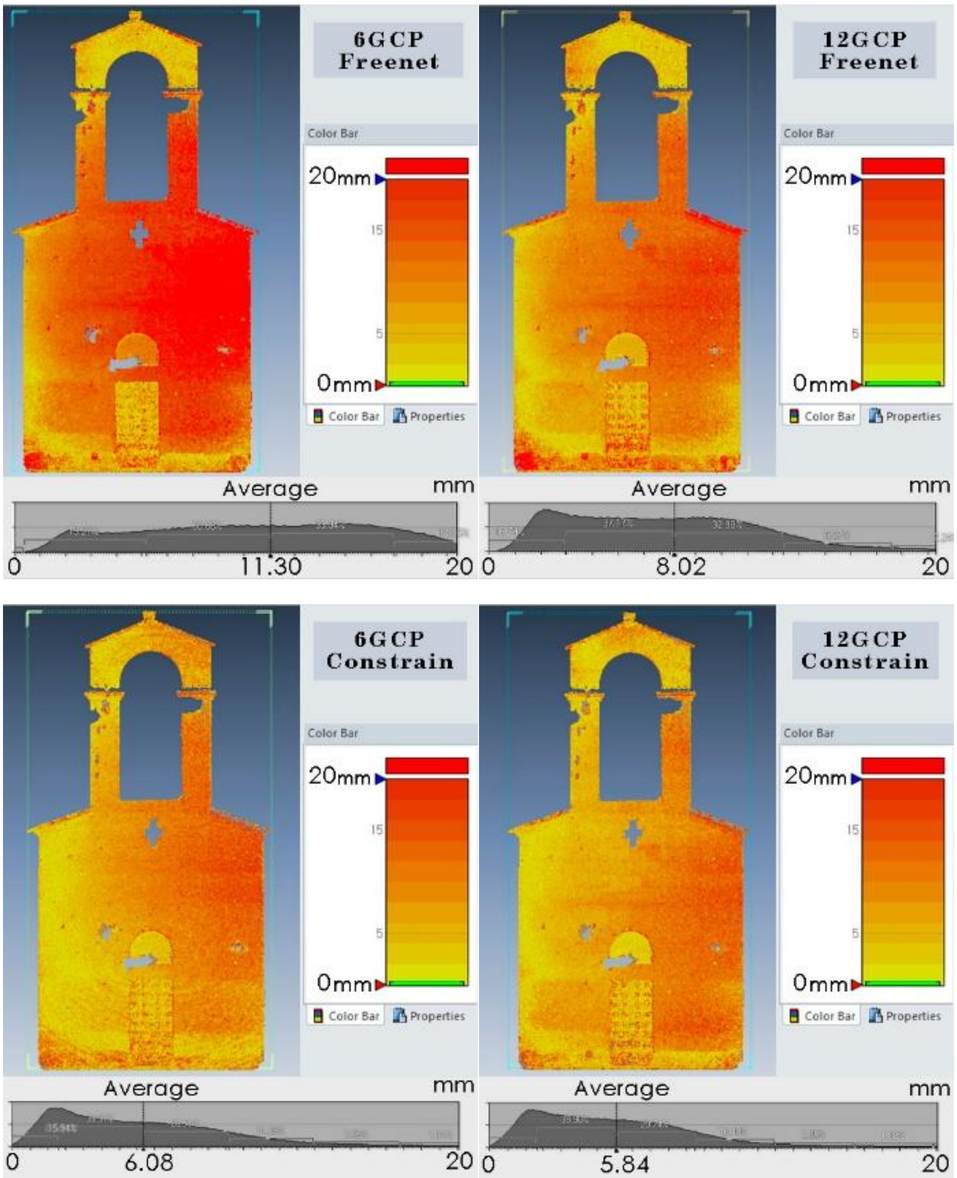

Figure 4.14. Laser scanner – SfM/MVS model deviation

In this case, it was possible to compare the results obtained with the CPs comparisons. The trend was in accordance with the previous deviation analysis on the individual CPs.

It can be noted, however, that while in the comparison between virtual models, it was possible to observe the global deviation of the whole model, in the case of comparison by CPs it was possible to analyse separately the deviation for each of the axes of the model (x, y, z). This allowed to check if the deviation was greater in the plane of survey development (the perpendicular plane to the camera axis, XZ) or in depth (Y).

In the roof case, only one comparison was possible with the available resources, due to accessibility issues. As shown in the different case studies, sometimes this option was the only viable one in order to carry out accuracy tests. Thanks to this comparison methodology, it was possible to verify the influence of the GCPs both when their layout was changed and in the two main configurations for bundle adjustment (FreeNet and Constrained).

4.2.3.3. Harzburger Hof hotel

This case study is focused especially on the comparison of data, since emergency or structural instability situations may not always provide the optimal surveying conditions (excessive distance from the object, restricted access areas, limited field time, etc.). For all these reasons, it is necessary to have highest possible control of data reliability (Martínez-Espejo Zaragoza, et al., 2017).

Post-processing software

Images were processed by Agisoft's Photoscan v.1.1.3 software to obtain the model, while TLS point clouds were managed and aligned via Leica Geosystems' 3D Cyclone and JRC's Reconstructor. Comparisons between point clouds were carried out using Cloud Compare GPL software, using M3C2 algorithm with the local model defined by the quadric function $Z = aX^2 + cXY + dY + eY^2$, with Z defined as the scanner axis.

Comparison of TLS and UAV- based photogrammetry models

Since some portions of the building had been surveyed with both methodologies, surveying performances were checked for accuracy in the case of reference points with sub-centimeter precision.

To this purpose, the photogrammetric point cloud was compared directly with the single laser scans in their original reference system.

The comparisons were carried out on the two laser scans L1 and L2 referring to the main façade of the building.

In order to rototranslate and scale the SfM-MVS model, GCP coordinates were measured directly on the TLS clouds. Five points were selected in both L1 and L2 on the sub-horizontal portions of the building, where higher rendering accuracy is expected on the photogrammetric model, according to the following criteria:

- From the TLS models, which lack RGB data, well-identifiable points were extracted, such as summits of railings (point 4, in L1 and L2) (fig. 4.15 right and 4.16 left), chimney masonry (points 1, 2, 3 in L1) (fig. 4.15 left) and gutters (point 5 in L1 and L2; points 6 and 8 in L2) (fig. 4.15 right, 4.16 left and 4.16 right).
- In order to improve detection of apparent vertices, cloud normals were computed, so to exploit inclination colouring, which highlights changes in plane sloping.
- Points on the ground were avoided, due to poor detectability on TLS clouds, as well as points close to vegetation.
- Points selected via image detection were collimated in the Photoscan environment.

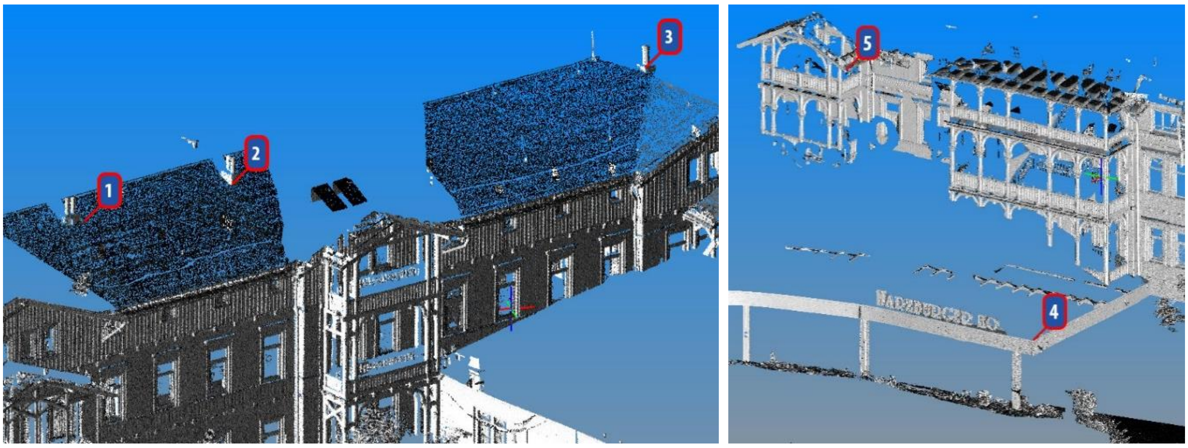

Fig. 4.15. Points 1, 2, 3 on L1. Vertices of chimney masonry (left). Points 4 and 5 on L1. Vertex of garage wall (point 4) and of roof (point 5) (right).

Fig. 4.16. Points 4, 5, 6 on L2. Vertex of garage wall (point 4) and of roof (points 5, 6) (left). Points 7, 8 on L2. Vertices of roofs (right)

Once the point clouds had been framed in the same reference system, processing was carried out according to the following steps:

- Creation of the CloudCompare project: the rototranslated block was exported in the "*.ply" (binary) format, which holds geometrical information along with RGB data and 3D normal data (nx, ny, nz). This was read and managed in CloudCompare.

- Point cloud cleaning: the point cloud was purged from vegetation, isolated points and points specific for either cloud. To this purpose, cutting polylines and common masks were set up in order to delete the same portions of space from all clouds.

For a more effective precision check, portions of point cloud were isolated from the models based on geometric homogeneity, considering firstly sub-horizontal portions.

Figure 4.17 shows the selected model portions: three roof flaps (T1, T2 and T3) and a vegetation-free ground portion (TR).

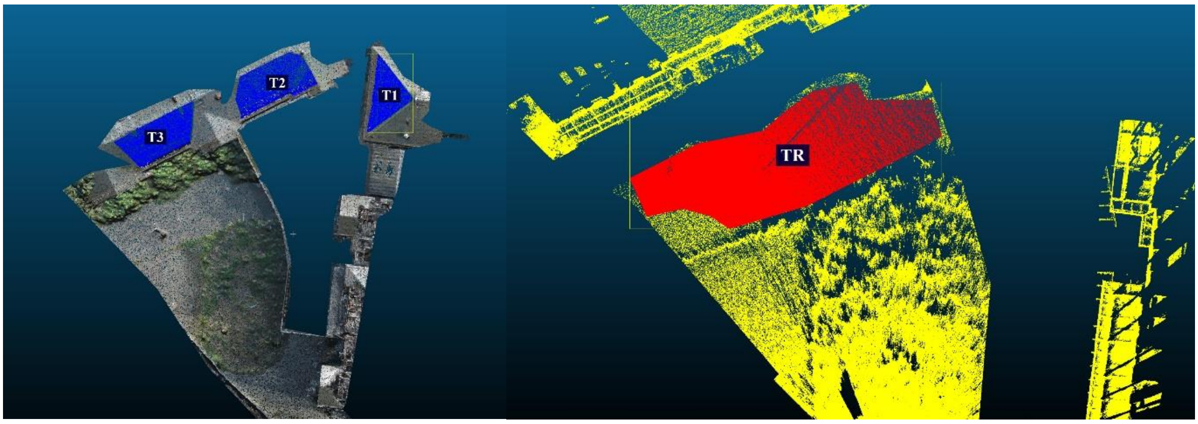

Fig. 4.17. Three roof flaps (T1, T2 and T3) (left) and a vegetation-free ground portion (TR) (right)

Subsequently, vertical walls without (V1 and V2) and with (AG1 and AG2) projecting portions were also considered (fig. 4.18).

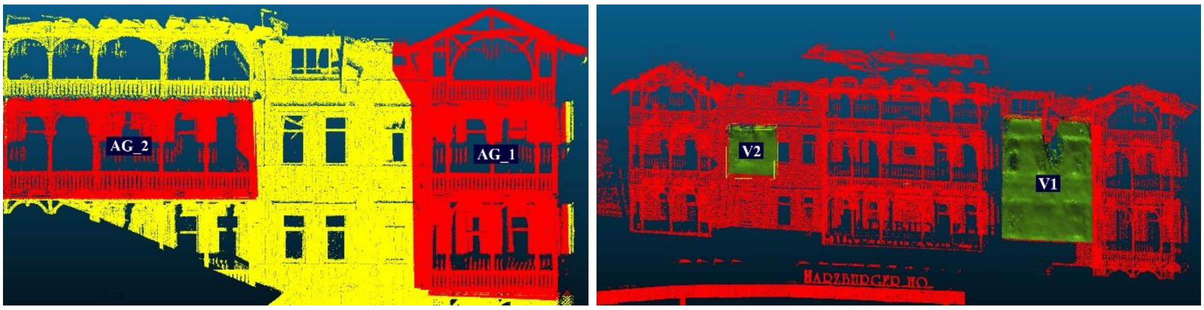

Figure 4.18. Vertical walls without (V1 and V2) (left) and with (AG1 and AG2) projecting portions (right)

Assuming TLS methodology as reference, the photogrammetric model was then checked for precision, applying cloud-to-cloud check algorithms.

Results

The original methodology introduced indicated how operator input of tie points improved the model considerably (numerical results in tables 4.11 and 4.12, 4.13 and 4.14 of section 4.1.4.2)

Photogrammetry expresses most of its potential in terms of precision when surveying objects mainly extending on a plane orthogonal relative to the shooting axis. The case of T*n* and TR zones is an appropriate example.

However, images also included vertical parts, which are of course viewed with a small observation angle.

The photogrammetric model was also checked for precision on these portions, differentiating between simple vertical walls (V) from those featuring projecting parts (AG).

Tables 4.17 and 4.18 summarize the results of these comparisons. As expected, standard deviations are greater than those verified for sub-horizontal elements.

VERTICAL WALLS			
Reference	Compared	Mean [m]	Standard deviation [m]
L1_V1	SFM_B_V1	0.045	0.069
L2_V1	SFM_B_V1	0.056	0.064
L1_V2	SFM_B_V2	0.043	0.041
L2_V2	SFM_B_V2	0.037	0.030

Table 4.17. Comparison of V*n* between TLS and SfM_B clouds

PROJECTIONS			
Reference	Compared	Mean [m]	Standard deviation [m]
L1_AG_1	SFM_B_AG_1	0.081	0.113
L1_AG_2	SFM_B_AG_2	0.063	0.077
L2_AG_1	SFM_B_AG_1	0.085	0.102
L2_AG_2	SFM_B_AG_2	0.071	0.072

Table 4.18. Comparison of AG*n* between TLS and SfM_B clouds

This methodology allowed to observe the accuracy changes of the model depending on the surveyed zone. Thus, the decreasing accuracy was confirmed in areas not optimal for each specific technique. This will allow to check if the precision level is suitable to perform an integration, and in this case, know the lower precision of those parts not favorable to the survey.

4.2.4. Bibliography

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4.3. TLS/SfM-MVS INTEGRATION

4.3.1. Introduction

This thesis examines several case studies suggesting possible integration applications that address several surveying problems. In the first cases (Palazzo Roncioni vault and partially San Miniato), analysis of laser scanning and Image-based modelling techniques, studying the potential and limitations for each of them, entailed the need for their merging to obtain an accurate complete model at both morphological/topological (TLS) and texture levels (Image-based modelling). However, other case studies (San Miniato, Harzburger Hof and San Francesco) show that integration is not always necessary to achieve that objective, but other situations may occur requiring to add other techniques in order to obtain a more complete model.

The new survey tools used in studies aimed at architectural heritage preservation, natural disasters management, environmental planning, and so on, often show some dilemmas (Martínez-Espejo Zaragoza, et al., 2014). Several studies have confirmed that TLS surveys allow obtaining three-dimensional models of high accuracy at morphology and topological levels (Adembri et al., 2011, Benedetti et al., 2010, Guidi & Remondino, 2012). Currently, however, chromatic quality for laser scanners is not comparable to geometric quality, including scanners with built-in cameras. While high chromatic quality can be achieved through techniques of Image-based Modelling, models generated by these lack a homogeneous accuracy as to geometry, even though the results obtained by Computer Vision software make this approach increasingly viable (Biosca Taronger, et al., 2007, Guidi et al., 2010, Vidal & Martínez-Espejo Zaragoza, 2011, Merlo, et al., 2013, Wenzel, et al., 2013).

For both photogrammetric and laser-scanning data, pipelining is split in two blocks, one in the field, i.e. data collecting, and the other in the lab, i.e. data processing and production of graphical output, both 2D and 3D. These allow analysing the survey object from both geometric and graphical standpoints. However, each block has different features based on the methodologies used for surveying.

In SfM-MVS techniques, as commented previously, data collection includes camera calibration and network (planning and picture shooting), while data processing includes (Abdelhafiz, 2009, Manferdini & Remondino, 2010): (a) using bundle adjustment algorithms, for semiautomatic computation of parameters for external and internal camera orientation; (b) 3D restitution and surface generation; (c) quality analysis of results; (d) texture mapping and visualization.

In laser scanning techniques, data collection only includes the network step, whereas data processing includes alignment, merging and mesh generation, mesh editing, post-processing and generation of photorealistic textures (Apollonio & Remondino, 2010, Guidi, Russo & Beraldin, 2010).

On the other hand, it should be noted that, in order to generate models with high chromatic resolution and high geometric accuracy, well-defined conditions must be granted. As regards SfM-MVS techniques, lighting must be homogenous, frame overlap must be greater than 70%, an ideal shooting base/range ratio (1/3 – 1/4) would be strongly advisable and both normal and convergent imaging geometries should be provided.

As to laser scanning surveys, scans must overlap for at least 20% if using 'matching' scan registration mode, otherwise at least three targets (with known coordinates) must be visible in each scan. RGB data collection requires homogenous, diffused light; besides, the highest attention must be paid in avoiding data loss due to shadowing.

Actual surveying conditions do not always meet these ideal requirements.

4.3.2. Morphology and texture integration.

As regards the Palazzo Roncioni case study, a laser scanning survey of the vault was carried out. The accuracy attainable with TLS is well-documented and exceeds the requirements of the case study. However, one of the goals was achieving a virtual model with good morphological resolution and high colour quality. Upon completion of the survey and generation of the 3D model, it was obvious that the latter goal was not achievable using only a laser scanning survey.

In many cases, particularly in the context of architectural survey, good quality, photo-realistic textures must be used to apply to the model (Martínez-Espejo Zaragoza, et al., 2014).

These textures are not meant solely as aesthetic completion of the model but as an added tool allowing easier identification of details when using the model as an object of measurement.

In fact, after applying a texture to surface models, collimation of points is perceptively driven by the texture itself rather than the underlying geometry.

Applications involving the use of TLS or SfM-MVS models may require textures with the same level of geometric precision of the models they will be applied to.

These requirements are met by a few different surveying and rendering methods.

Many of the laser scanners have built-in cameras, whose relative orientation is calibrated by the manufacturer, which allow direct true colouring of the point cloud. These textures feature high geometric accuracy, but results in terms of resolution and colour fidelity are not as good (Apollonio & Remondino, 2010).

Simplified, realistic-looking models may not suffice e.g. for restorers, who require rigorous rendering in both morphology and colour information.

In these cases, it is essential to resort to a dedicated photographic campaign, executed with high quality cameras as regards optics, sensor size and post-processing graphics.

Before the Image-based techniques emergence, the traditional steps to obtain textures from these photos started by deriving camera features from a single take. Next, UV maps were generated using the so-called texture mapping (Guidi, et al., 2010, Baldissini, et al., 2010, Apollonio, et al., 2010) of the projection of single-frame models, and finally the different partial UV maps were merged in order to generate the texture of the model as a whole. Textures obtained in this way allow for 3-D models featuring high quality at geometric, morphological and chromatic levels (Fantini, et al., 2012).

On the other hand, this procedure is very time-consuming, also requiring constant operator intervention in the collimation of the points on the model and on photograms. In addition, software and procedures commonly used quite often do not take into account the distortion present on photograms.

In the case of SfM-MVS software, creation of models and textures is pretty much contextual, and procedures usually involve camera self-calibration, which also takes account of characteristic distortion parameters. These models usually feature textures with good photographic quality, although, as stated above, their overall morphological reliability is not comparable to TLS models.

4.3.3. Morphology integration

As already commented, by using and integrating laser scanning and SfM and MSV techniques, it is comparatively easy to obtain complete models with centimetre accuracy and photorealistic textures (e.g. Caroti, et al., 2015, Fantini, et al., 2012, Meschini, et al., 2014.) (Martínez-Espejo Zaragoza, et al., 2015A). However, these considerations apply just in cases presenting the ideal conditions for each survey technique. As regards Palazzo Roncioni and the façade of San Miniato, conditions were right and it was possible to use both techniques to obtain an optimized model. On the other hand, due to operating conditions or limitations of the technique itself, it was necessary to combine both techniques in order to obtain a complete morphological model for the roof of San Miniato and in the cases of Bad Harzburg and Ferrara. In the San Miniato case, as the problem was linked to the physical impossibility of access to the roof, UAV-based photogrammetry was exploited (fig. 4.19). Both the Ferrara and Bad Harzburg cases presented emergency and structural instability issues. In the latter, the UAV-based photogrammetry was also used.

Figure 4.19. UAV capturing the façade of the church.

Thus, even though use of SfM-MVS and/or laser scanning, either as standalone or integrated techniques, enables achievement of complete, high-quality surveys, in some cases peculiar layouts of the working environment may prevent the application of standard methodological procedures (Martínez-Espejo Zaragoza, et al., 2015A).

In order to generate models with high chromatic resolution and high geometric accuracy, well-defined conditions must be granted, as already explained in section 4.3.1.

However, in most of the surveys performed in areas struck by natural disasters or with difficult access, many of the above-mentioned conditions are not attainable (Fassi, et al., 2015, D'Amico, 2001).

Shallow passageways and/or inaccessible areas decrease the overall ability to effectively use collection points designed for optimal results (Rodríguez-González, et al., 2015). On the other hand, total lack of lighting implies use of artificial lighting sources, whose reverberation negatively affects the performance of most of the cameras integrated in laser scanners. Scarce or uneven lighting also negatively influences surveys involving Image-based techniques. A possible solution to accessibility problems in certain cases comes with the introduction of UAVs as best option. At times, safety-related problems may hamper proper positioning of the instruments. All these situations test the conditions required for suitable survey operation, and in many cases make it impossible. These cases (when some of the above conditions are present) require not only survey planning and execution according to classic standards, i.e. choice of technique/methodology and their correct deployment based on accuracy requirements, but also to detect and apply different surveying techniques based on the ability of each and every technique to fill in for any operating shortcomings of the others, rather than their inherent features (Koska & Křemen, 2013, Martínez-Espejo Zaragoza, et al., 2017).

In emergency conditions, logistics and safety issues may sometimes require application of these methodologies beyond best accuracy boundaries in order to obtain a geometrical model as comprehensive as possible of the scene, which will provide the basis for subsequent interventions.

Such conditions require using areas surveyed with suboptimal reliability by each of the methodologies. As an example, it can happen that some sub-horizontal or gently sloping areas, such as roofs, are surveyed only via TLS, i.e. with a very small incidence angle of the laser beam or, vice versa, that vertical walls are surveyed only by UAV-borne photogrammetry with nadiral shooting axis.

Thus, combined use of these techniques is proposed as an original methodology, in which each of the steps that compose it is studied carefully and checked for accuracy, in order to solve mentioned issues where either technique will not achieve adequate results on its own.

4.3.4. Case studies

4.3.4.1. Palazzo Roncioni

This case study (Martínez-Espejo Zaragoza, et al., 2014) proposes a different way to obtain texture models with high quality levels for geometry, morphology and colour, taking advantage of the strictness of 3D models produced from laser scanning surveys, and of the quality of textures derived from sets of photograms oriented with dedicated SfM-MVS software.

The basic concept was to use laser scanning surveys as the geometric foundation. Regarding the texture, a campaign of dedicated photographs was completed and, rather than orienting and projecting each one individually, SfM-MVS software was used not so much for generating models, as for its ability to automatically detect numerous sets of homologous points and to solve the problem of calculating the orientation parameters (camera features). Finally, the model generated by the laser survey was imported in the same SfM-MVS software used for camera orientation and had the images projected on it. As a case study for this methodology, a frescoed vault under restoration was chosen.

Although the model generated by the 3D photogrammetry technique was not used as is, it was necessary to test its accuracy. If models lack an acceptable accuracy, so will the orientation parameters calculated from the cameras in use. Therefore, within the workflow of the case study a section was dedicated to analyse the accuracy of both TLS and SfM/MVS models. If compatibility of both is confirmed, it is possible to continue and project the Image-based modelling texture on the TLS model.

Projection of individual images on the model

A methodology to provide models with colour maps consisting of photo-realistic textures was based on the projection of the individual photographs on the mesh.

Upon completion of the photogrammetric campaign, the steps to follow included collimation of tie points in a reverse modelling software, collimation of the same points to orient the images using photogrammetric software and finally definition of the texture through a software for entertainment.

In the survey-planning phase, the surface of the vault was divided in 6 regions characterized by almost constant curvature (see section 4.4.2.2 and Figure 4.29 for further clarifications); for each of these, 12 photographic images were collected, keeping the optical axis close to the direction of the radius of curvature of the centroid of each area. The photograms had to ensure full coverage of the object taking into account that only the central portion of each photogram was used in order to avoid residual radial distortion at the edges.

The processing procedure was the same for each photogram to be projected.

Considering the part in common between the photogram and the 3-D model obtained from laser scanning, a set of tie points was selected so that their distribution was as uniform as possible. These were exported as coordinates in DXF format, using a point cloud management software of the TLS model (e.g. Rapidform XOR3, fig. 4.20 left). These coordinates constituted the Control Points (CPs), which the photogrammetric software (e.g. PhotoModeler) used to orient the photogram. Photogrammetric software was used to derive the image coordinates of the chosen tie points (fig. 4.20 right); it was also possible to calculate the camera features along with the precision with which the various parameters were determined.

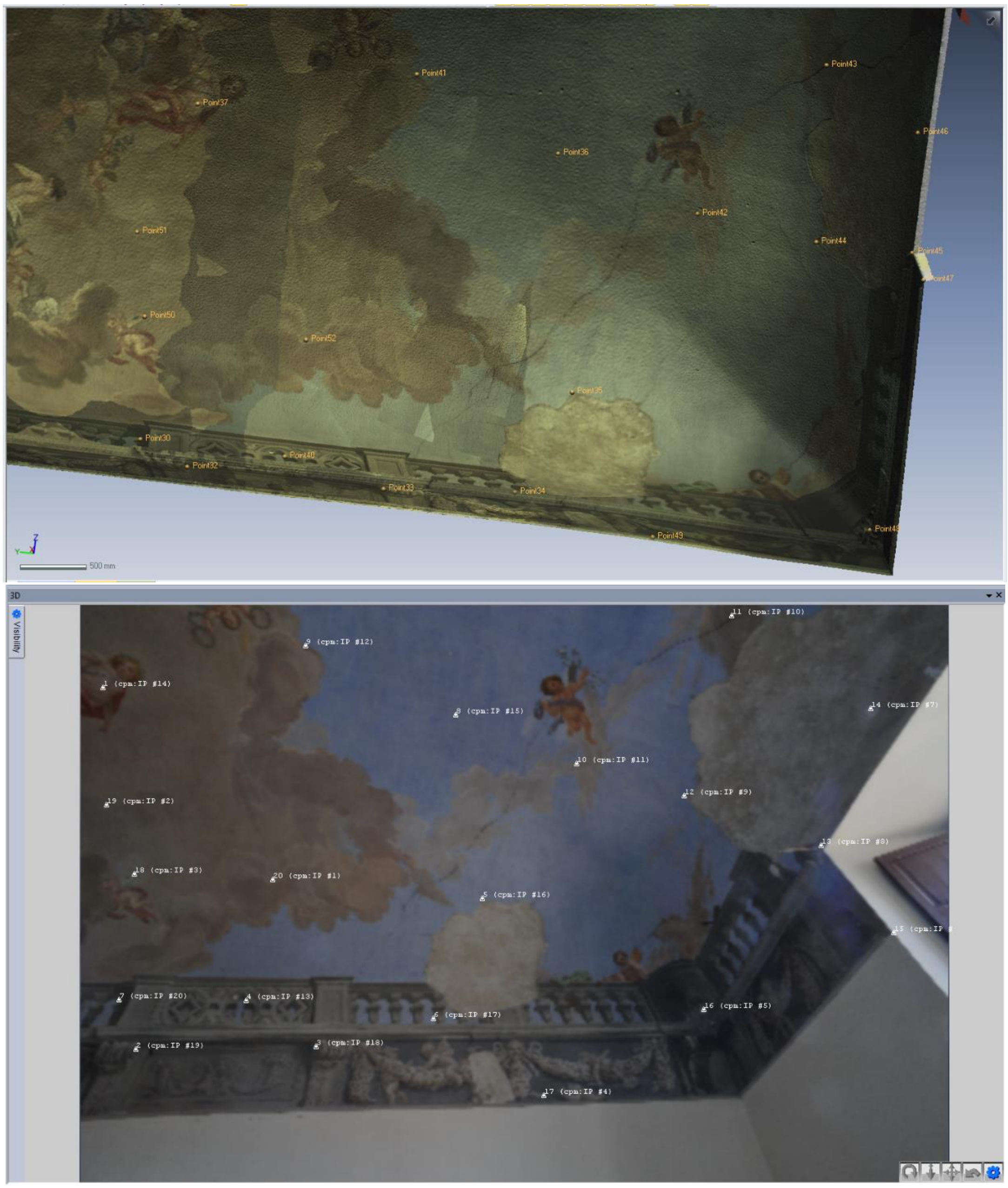

Figure 4.20. Homologous points on the 3D model (above) and the photogram (below)

Repeating this process for all the photograms yielded the orientation parameters of the cameras, each of which was exported in a format compatible with the entertainment software used for texturing (e.g. Luxology Modo - format *.fbx).

Upon importation into the entertainment software, the so-called subdivision surfaces model were created in order to texturize the model (Fantini, 2012); the related UV map was also defined (fig. 4.21).

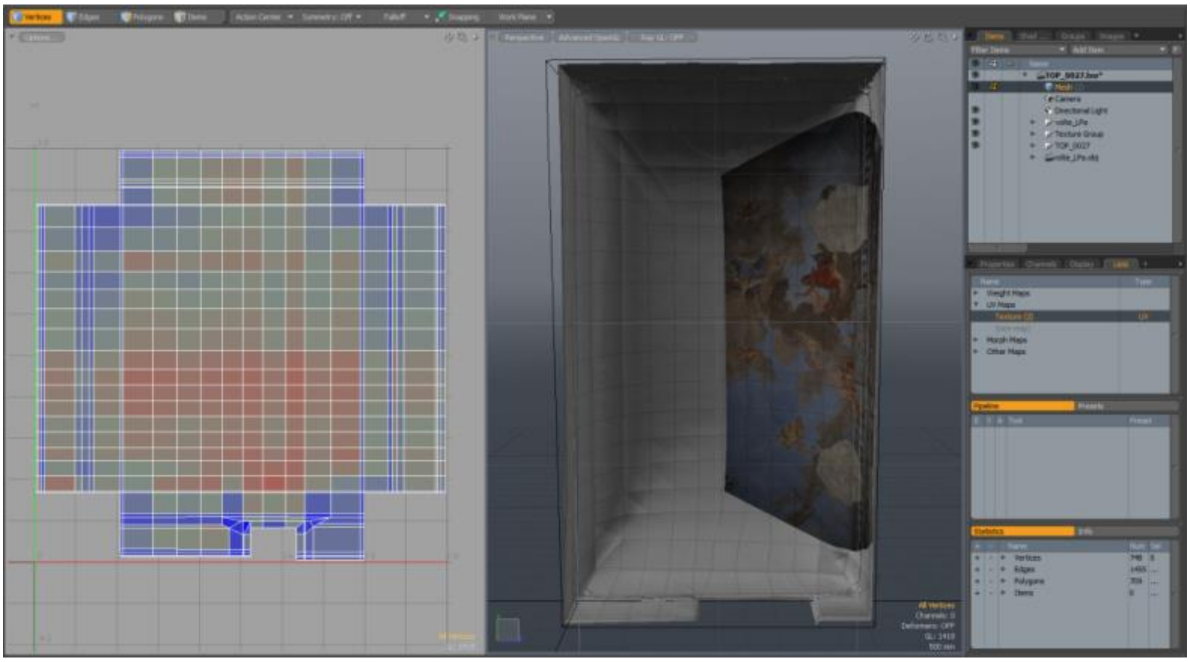

Figure 4.21: UV map of the subdivision surfaces model with projection of a single photogram.

By projecting individual photograms, partial UV maps were obtained (fig. 4.22 left) applying colour only to the framed part of the vault. At this point, all partial UV maps had to be reprocessed with a photo editing software (e.g. Photoshop), merging them into a single image (fig. 4.22 right). In this operation, the different images were processed in order to produce uniform brightness, contrast and saturation, and to select the corresponding portions of UV partial map for the central portion of the respective photograms to reduce the influence of the residual radial distortion. Finally, the overall UV map was projected onto the laser model using entertainment software.

Figure 4.22: Partial UV map of a single photogram (above) and total overall UV map (below)

Creating a model with SfM/MVS techniques

Generation of the model through SfM/MVS techniques was performed by means of a dedicated photogrammetric campaign. This was necessary because, while as previously described for texturing the photograms are just required to cover the entire surface ensuring a low mutual overlap, SfM/MVS techniques requires an overlap between photograms of at least 70% in both directions. In this respect, SfM/MVS techniques differ from classic photogrammetry, where processing is carried on by strips, and a greater overlap for adjacent strips is required only in the longitudinal direction. The new photo campaign was carried out with the same camera and the same optics as the previous one. The SfM/MVS software used in this test was Agisoft's PhotoScan 1.0.0. The development followed the steps provided by all software of this type, i.e. camera calibration, image orientation, dense point cloud generation, surface generation and texture mapping and visualization (Manferdini & Remondino, 2010).

The result of processing was a 3-D, high colour resolution model (fig. 4.23 left), but with a lower quality mesh as for morphology and geometry (fig. 4.23 centre) compared to that obtained from processing of the laser scanner survey (fig. 4.23 right).

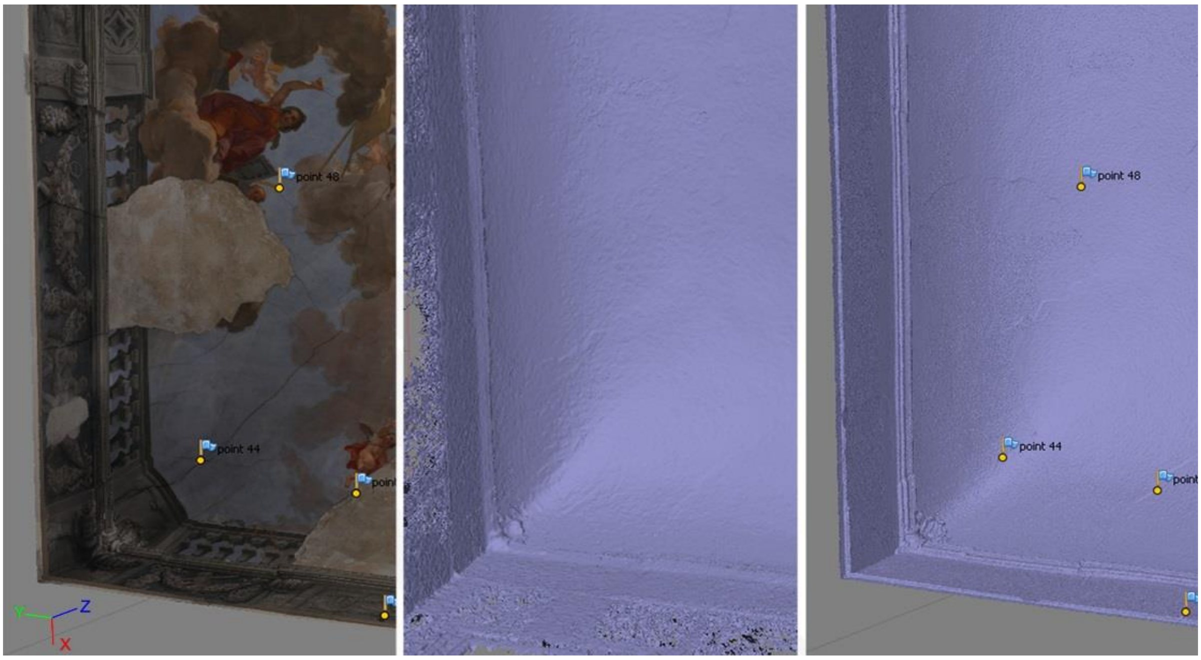

Figure 4.23: Texture from SfM/MVS (left), model from SfM/MVS (centre) and model from laser (right)

Projecting the image-oriented model on laser models

It should be emphasized that the lower geometric quality of the 3-D model obtained with SfM and MVS techniques as described in the previous paragraph is due to the ability of the method to faithfully reproduce local morphological changes at a small-scale, rather than its ability to render the overall geometry of the survey object. Partial results of SfM/MVS modeling were used, i.e. camera orientation parameters; images were projected on the most faithful model obtained from laser scanning. It should also be pointed out that, in order to use this methodology, both models were framed in the same reference system.

The laser scanner model was then imported into SfM and MVS software and had the photo-realistic texture applied. (fig. 4.24).

Figure 4.24: Laser scanner model textured via SfM-MVS software

Geometrical comparison between TLS and SfM/MVS model

Since the comparison between the two mesh models (fig. 4.25), with the TLS as reference, and the other resulting from SfM-MVS software, show that the latter is strongly dependent on the pattern present on the vault, it was not possible to ensure a homogeneous local precision in rendering small morphological variations. Greater deviations (varying in absolute value between 7 and 10 mm), coincident with cracks or margins of plaster collapse and gaps in the fresco, are quite obvious. This should be considered when integrating models, in order to check the possible accuracy decrease in such areas.

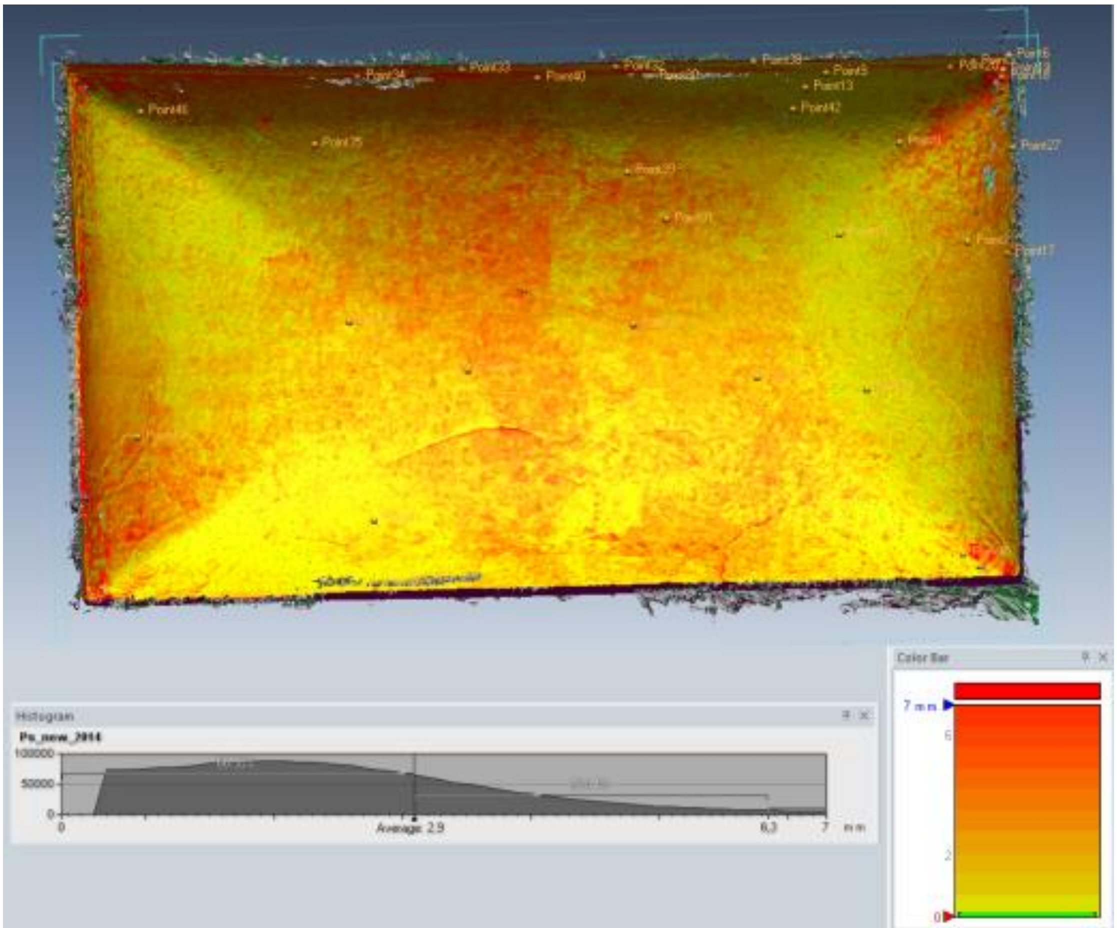

Figure 4.25: Distance in absolute value between mesh models obtained from laser scanner survey and from SfM/MVS software

Texture precision of final model

The laser scanning model, coloured from the data of the built-in camera, may be held as a reference for both geometry and 3-D texture placement. An analysis of the deviation of the 3-D position of points in the texture between the reference and the SfM/MVS models was subsequently carried out, involving a set of 20 points evenly distributed on the vault and resulting in a standard deviation of about ±3.5 mm. This comparison was necessary for the precision irregularities in the SfM/MVS model, observed in the areas of greatest interest.

Conclusions

The proposed methodology allows to obtain a 3-D model featuring both the geometric strictness of laser scanning surveys and the quality of textures obtained with photographic survey campaigns.

The most interesting aspect highlighted by the application of the methodology proposed, is considerable savings in terms of time and resources compared to the traditional methodology of orientation and projection of individual images on the model (table 4.19). In addition, from the point of view of positioning precision of the textures, both procedures displayed roughly the same accuracy.

SINGLE-IMAGE TEXTURING	**SFM/MVS TEXTURING**
Survey planning	Survey planning
2 – 3 HOURS	3 – 4 HOURS
Photo campaign fieldwork	Photo campaign fieldwork
1 HOUR	2 – 3 HOURS
Processing steps for each image	Processing steps on image set
Definition of tie points by collimation in a reverse modelling software Image orientation by collimation of the same points via photogrammetric software Definition of camera position relative to TLS model via entertainment software	Image alignment Dense Cloud generation Mesh generation Texture generation
3 – 4 HOURS (per image)	3 – 4 HOURS (total)
Creation of subdivision surfaces model and related UV map (TLS model)	Input of GCPs in TLS coordinate system
4 – 5 HOURS	4 – 5 HOURS
Output of partial UV maps by projecting individual image	Import of TLS mesh
15 – 30 MIN (per image)	1 MIN
Merging of UV maps into a single image via photo editing software	Projection of texture onto TLS model
1 – 2 DAYS	30 MIN
Projection of overall UV map onto TLS model	
1 MIN	

Table 4.19. Process comparison for generation of textured models

4.3.4.2. San Miniato church

In order to achieve a complete model of the church, different survey techniques were used (Martínez-Espejo Zaragoza, et al., 2015B). These included terrestrial laser scanning (for surveying the inside and outside of the church, with the exception of the extrados roof, which was not accessible), aerial photogrammetry (for surveying the main façade and roof), terrestrial photogrammetry (for the application of photorealistic texture to the laser scanning model) and total station (to bind laser scanning and photogrammetry data with high precision).

The result of the integration of both, Image-based and Laser scanning techniques was a complete three-dimensional model (fig. 4.26).

Figure 4.26. Render of the church from integrated surveys

The geometrical precision obtained from TLS is in the order of 1cm. On the other hand, the graphic resolution of the applied texture is higher and coincides with the linear dimension of the pixel, in the order of 1 mm.

In parts where laser scanning surveys were not practicable (e.g. Roof), SfM/MVS methodology allowed the integration. The accuracy of the resulting roof model albeit not homogeneous, was comparable to that of TLS model. In addition, photographs used in SfM/MVS generate high-resolution textures.

A further advantage of integrated surveying was having a single reference system for all data. This allowed to build an information system of the architectural object, to which all documentation and georeferenced elaborations was referred.

Conclusions

The proposed methodology allowed to obtain a complete survey which can generate a three-dimensional model. So far, in historic buildings, whenever preliminary investigation was required for any further intervention, the survey of roofs involved high difficulty levels in both operative and economic terms. Accessibility issues are always one of the most conflictive in low budget survey.

The introduction of UAVs for the survey of roofs and areas with accessibility issues was a major advancement in job site safety, also allowing major reductions in costs.

The difference between SfM/MVS and TLS has been substantially reduced, since the reliability of the models of the first type is closely linked to the ability of the operator to appropriately structure the network (the position of the different cameras relative to the object). From this point of view, UAVs have been a major advance, allowing removal of one of the most common problems in photogrammetric surveys of closely placed elements, i.e. vertical plane shootings.

As an example, in standard buildings cameras can essentially capture the lower levels. Although zoom capabilities enable capture of wider areas, ultimately the object is developed mostly horizontally, and as a result the reliability of such a survey will be very high at the bottom and much lower on higher levels. The use of UAVs allows for a vertical development of network enabling documentation of the objects from many viewpoints. This in turn allows to approximate the precision of photogrammetric surveys to that based on laser scanning.

Models obtained with photogrammetric techniques have variable accuracy (depending on acquisition method, type of camera, medium - i.e. airborne or terrestrial photogrammetry - and software used in the process of elaboration), but, by using appropriate methodologies and by controlling the generating processes, may be suitable to integrate data collected with different instrumentation such as terrestrial laser scanners, Total Stations, GPS, etc. Therefore, SfM/MVS techniques can be considered a good method for integration with other methodologies. Integration of models, and consequently of modelling techniques, is essential for analysis both architectural and related to interventional techniques.

4.3.4.3. Harzburger Hof hotel

As already stated, metric surveys in areas presenting safety issues require following non-standards procedures so to be able to fill in for any operating shortcomings of any single technique exploited, rather than their inherent features (Koska & Křemen, 2013).

In emergency conditions as outlined for the present case study, logistics and safety issues may sometimes require application of these methodologies beyond best accuracy boundaries, in order to obtain a geometrical model as comprehensive as possible of the scene, which will provide the basis for subsequent interventions.

Such conditions require to work with areas surveyed with suboptimal reliability by each of the methodologies. As an example, it can happen that some sub-horizontal or gently sloping areas, such as roofs, are surveyed only via TLS, i.e. with a very small incidence angle of the laser beam or, vice versa, that vertical walls are surveyed only by UAV-borne photogrammetry with nadiral shooting axis.

In the present case study, these areas, which represent criticalities for either methodology, were surveyed via both TLS and UAV-borne photogrammetry, with horizontal flights and nadiral shooting axis.

Results in tables 4.13 and 4.14 in the section 4.1.4.2. show how use of UAV-based photogrammetry and data processing with SfM/MVS algorithms can provide models with comparable precision as those obtained via TLS, and therefore can integrate the latter for else unavailable data.

Conclusion

Results presented in section 4.2.3.3. show how, in case of necessity due to emergencies, integrating TLS with UAV-based photogrammetry is quite effective.

It has been shown that precision of UAV-based photogrammetry is comparable to that of laser scanning in parts lying almost orthogonally to the shooting axis. In this case study, it provides an effective solution to integrate the survey of roofs, garden and inner courts, where stability issues prevent accessibility.

On the other hand, UAV-based photogrammetry with nadiral axis provide lower quality on vertical parts.

However, the possibility to use UAV-based surveys to process also portions acquired with limited view angle, such as vertical walls, is surely interesting.

In fact, as the rendering scale for these portions will not be the same as for sub-horizontal parts, the survey allowed the restitution also of all inaccessible and vertical internal walls of the building.

4.3.4.4. San Francesco church (Ferrara, Italy)

The survey of the object of this case study was also performed in an emergency, posing similar problems such as instability, restricted access areas, narrow passageways and so on. This situation required the use of both methods (TLS and SfM/MVS) to obtain a more complete model, although in this case both techniques are land based due to the interior setting (Martínez-Espejo Zaragoza, et al., 2015A)

Data processing workflow generally included processing of TLS point cloud, which was used as a geometric reference for surface generation and image projection on the mesh for high-resolution texturing.

Subsequently, photographic data was processed, computing shooting geometry for the cameras and reconstructing the point cloud via SfM-MVS algorithms. The survey was then framed in the TLS reference system, through well-identifiable control points on the walls. Anyway, when the reference laser mesh showed some problems (as those mentioned in the following paragraph), photogrammetry data was checked and subsequently used for surface generation (fig. 4.27).

AREA	Aisle	Wall	N. scans	N. Photograms	Mesh	Texture
Aisle LX	Aisle outer Vault	wall 1	20	165	Laser scanner	Photoscan
		wall 2		24	Laser scanner	Photoscan
		wall 3		217	Laser scanner	Photoscan
		wall 4		26	Laser scanner	Photoscan
	Aisle inner Domes	wall A	26	14	Laser scanner + Photograms	Photoscan + Laser scanner
		wall B		57	Photograms	Photoscan
		wall C		1061	Laser scanner	Photoscan
		wall D		45	Photograms	Photoscan
Aisle RX	Aisle inner Domes	wall B	19	46	Photograms	Photoscan
		wall C		299	Laser scanner	Photoscan
		wall D		33	Laser scanner	Photoscan

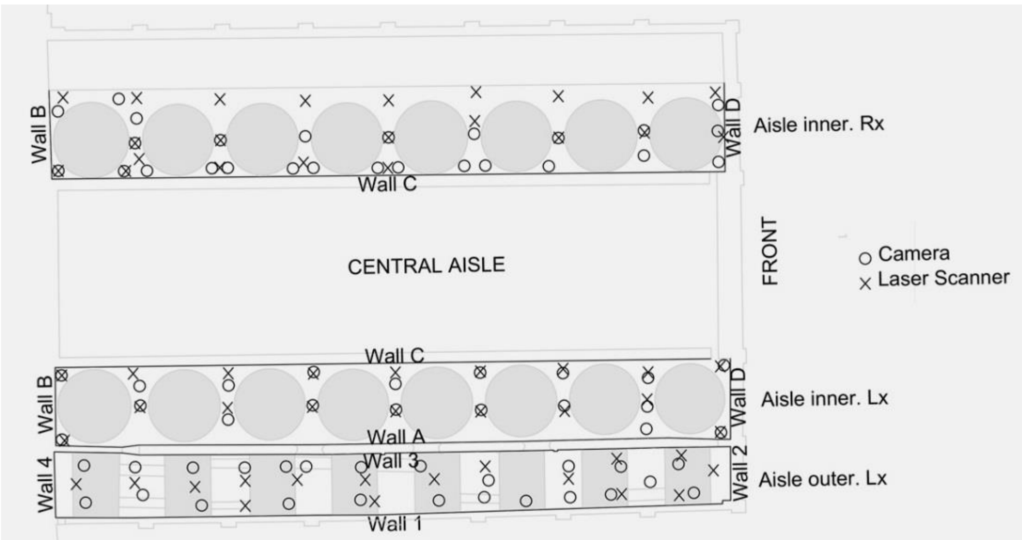

Figure 4.27. Processing methods (above) and instruments layout (below).

In some cases, laser scanning point clouds were very noisy, due to high concentration of dust in the attics, which requires frequent breaks to blow the scanner mirror clean. In other cases, meshes showed some geometric issues as missing parts or noise; in some scans, problems due to vibration were also reported. The wooden walkways installed for security purposes turned out to be unstable and sensitive to any movement.

In fact, the short sides had so little operating space that the scanner could not be properly positioned, as the distance between scanner and wall was less than the minimum operating distance (about 60cm). In these cases, the resulting gaps in TLS meshes hindered their usability. On the other hand, issues in photo shooting resulted in poor overlap in some areas, which effectively prevented the generation of a point cloud with verifiable accuracy.

In order to overcome the absence of data in the laser mesh, a procedure for integrations of photogrammetry and laser-scanning data was devised. Whenever a gap in the laser point cloud was detected, the surrounding area was extracted and locally compared with same area in the photogrammetric cloud, which was already framed in the same reference system. The clouds were subsequently aligned by means of the Iterative Closest Points (ICP) algorithm, and if the iterative procedure yielded a sub-centimetre Root Mean Square (RMS), photogrammetric reconstruction was accepted and data sets were integrated.

Upon correct integration of the point clouds, the next step included orthoprojection of photograms on the laser mesh, except for the noted cases.

Point clouds derived from laser scans were instead used for extraction of 2D graphical output.

Conclusions

Integration between terrestrial laser scanning and photogrammetry is a well-established surveying practice. The present study analysed a case in which the single methodologies are aimed at the final product, rather than aesthetic purposes. In this case, integration of laser scanning with photogrammetry has proved useful, beyond improvement of graphical quality, to make up for missing data in the laser survey. Possible future developments for the present work could include the definition of a methodology enabling validation of the integration as proposed, in terms of expected and attainable precision.

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4.4. ORIGINAL APPLICATIONS IN ARCHITECTURAL SURVEYS

4.4.1. Introduction

Image-based Modelling techniques, alone or integrated with Range-based Modelling, are particularly effective when applied to the analysis of historical buildings, in particular of special architectural complexes hardly detectable through traditional techniques.

Every case study presented its own peculiarities, which required continuous relations with experts having skills in similar fields. This, in turn, exposed new possibilities and goals, and ultimately led to the development of ad hoc applications.

Although certain limitations may be found on these ever-evolving techniques, they also offer increasing advantages and possible new applications.

For example, in the Palazzo Roncioni case, the restorers needed 2D vault development at 1:1 scale. Orthophotographs are a common output in 3D surveys, but their projective nature prevents their use as support in drafting fresco outlines, as required by restorers. This development can be easily performed on simple developable surfaces, such as barrel or ribbed vaults. However, on complex surfaces, the problem is not solvable in automatic mode.

In other cases, the possibility of obtaining an integrated model with high morphological accuracy and high colour resolution allows to perform pathological studies without having to spend several days at the site, detecting pathologies *in situ*. This also is crucial in emergency, where security is one of the most important factors to consider (Martínez-Espejo Zaragoza, et al., 2015A). Moreover, with the use of UAVs, the problems linked to the small scale (if aerial photogrammetry is necessary) are removed, as is the need to use cranes or scaffolding for image acquisition to execute large scale surveys of non-accessible areas (Martínez-Espejo Zaragoza, et al., 2015B). In the Harzburger Hof hotel case, security issues and the subsequent exploitation of UAV-supported surveys required yet another approach to data integration (Martínez-Espejo Zaragoza, et al., 2017).

In all these applications, with different scales and kinds of buildings, a new pipeline was introduced. In this new workflow, the three previous research aspects were considered allowing to achieve an optimized survey, where the accuracy of the acquired data was verified and several data were integrated with an accuracy control of both each model and the models obtained in the integration. Thus, some application proposals were developed using all available data from different processing stages.

4.4.2. Development of frescoed vaults

4.4.2.1. Vault Development (state of the art)

Commercial and open-source software currently available are capable to render architectures in 3D as regards formal appearance and colour as well as metric information (Bevilacqua, et al., 2016). On the other hand, operating steps of restoration interventions still require large-scale, 2D metric surface representations. The transition from 3D to 2D representation, with the related geometric transformations, has not yet been fully formalized and still features open issues, e.g., in the case of planar development of frescoed vaults (Carpiceci, 2011). Methodologies proposed so far on this subject provide transitioning from point cloud models to known mathematical surfaces (developed on plane, or not), and afterwards seeking an ideal representation of the actual surface, losing some architectural and building details in the process (Menna, et al., 2012, Cipriani, et al., 2011, Chiabrando & Rinaudo, 2014, Pancani, 2011, Cannella, 2015). To the best knowledge of the candidate, modelling and reverse engineering software commonly used lack-dedicated tools that enable automatic development of geometry and textures. Moreover, tools that only partially solve the problem do not take into account any introduced deformation.

4.4.2.2. Vault Development method

Point clouds, either collected by laser scanning (Cloud LASER) or obtained by photogrammetry (Cloud SfM/MVS), were framed in a single reference system. The *X*- and *Y*-axes lie in the hypothetical vault impost plan, which is not horizontal (axes origin in a corner, *X*-axis on the long side and *Y*-axis on the short side) and the *Z*-axis completes the orthogonal triplet. In order to proceed with the 2D vault development, the 3D model was analysed.

Analysis and Preliminary Processing of Laser Data

In order to define the geometric components that constitute the vault, a dense contour (step = 20 cm) representation of model LASER was generated according the three coordinate planes (fig. 4.28).

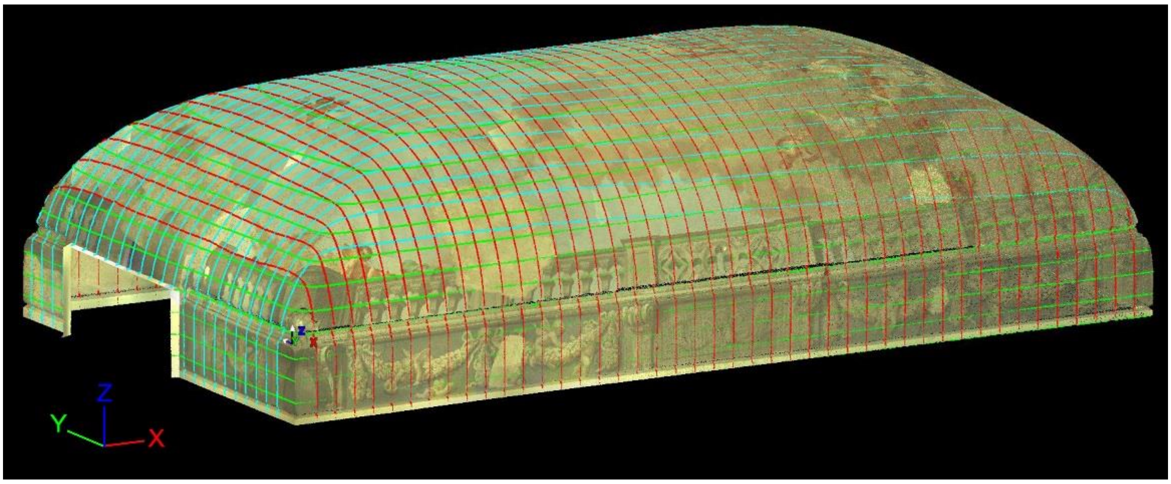


Figure 4.28. Dense contour model (isometric view).

The study of this contour representation (fig. 4.29) allowed identification of nine discontinuity directions dividing the vault in 6 areas, each featuring its own section profiles with almost constant radius: areas 2, 4 and 6, close to the vault impost, have greater section profile radii than those in the upper part of the vault (areas 1, 3 and 5). Separation between the lower and upper parts of the vault is located at about one third of the vault height above the impost plane.

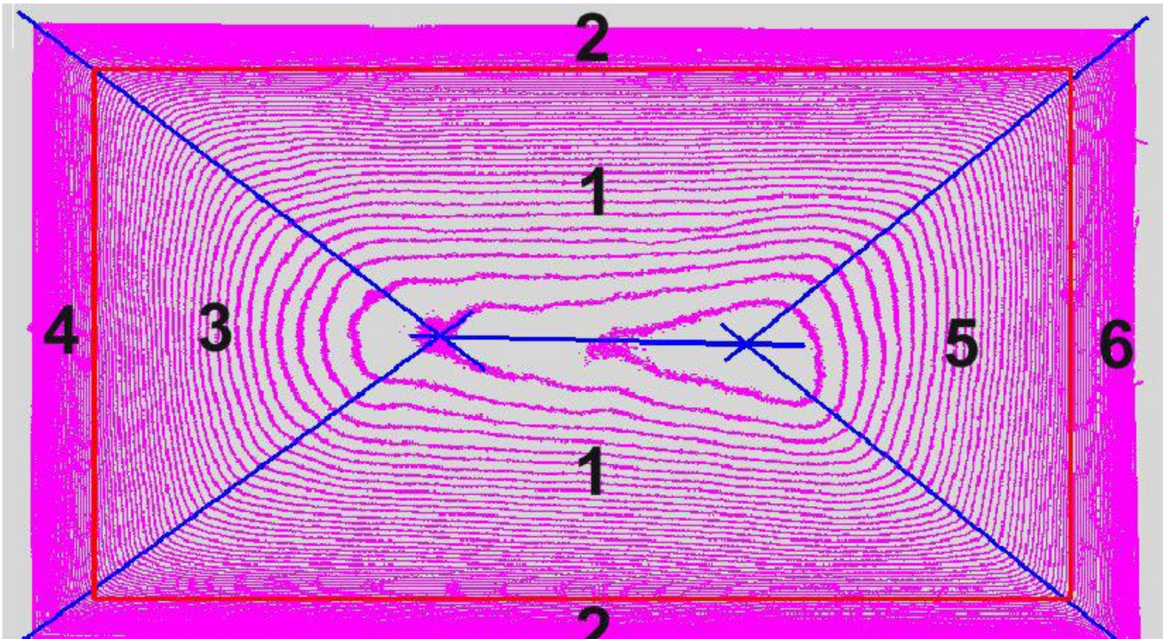


Figure 4.29. Discontinuity directions and vault areas (bottom view).

Interpretation of these results suggested that the vault could be generated from the combination of several elements belonging to different cylindrical surfaces, and could be part of the "*a schifo*" type. This includes a lower portion, similar to a section of a pavilion vault, and an upper one, named "*specchio*" (mirror), which features so wide a curvature to appear almost planar. This vault type has been widely used in architecture since Renaissance exactly in the case of fresco decorations.

Once the hypotheses about the building type of the vault were substantiated, the values of the geometric parameters (axis and radius) of the elementary cylindrical surfaces that best fit the point clouds of each of the six areas detected were computed by means of approximation algorithms.

As an example, approximation by cylindrical surfaces of the long side (fig. 4.30) yielded the following results (Table 4.20).

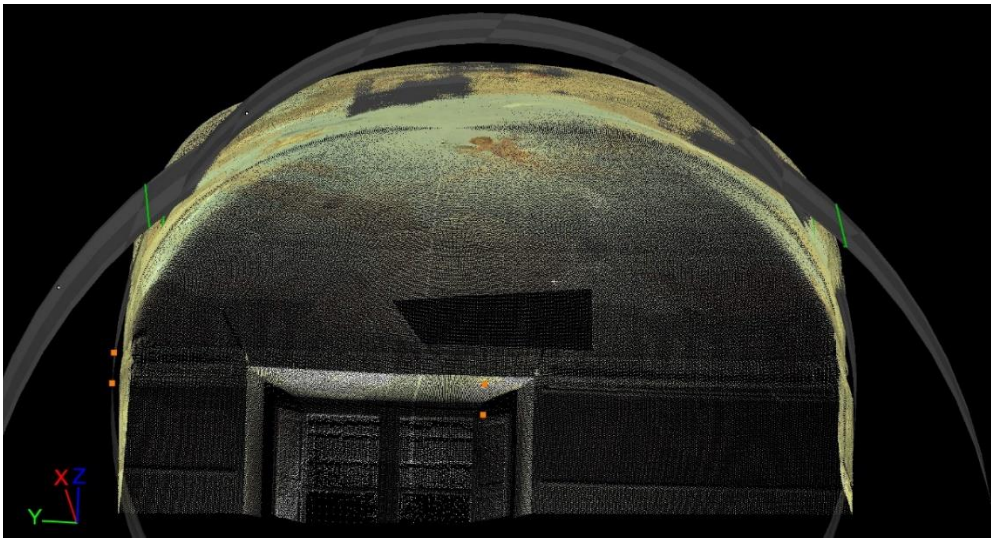


Figure 4.30**.** Approximation by cylindrical surface.

Table 4.20. Approximation by cylindrical surface—radius.

	Area 1	**Area 2**
Radius (m)	7.349	5.280
STDV (m)	0.007	0.008

Analysis of Standard Deviation (STDV) should take in account that the vault does not actually show neat transitions between contiguous cylindrical surfaces, but rather a transition curve. In fact, the higher values of the difference between ideal and actual surfaces were found in these transition areas (fig. 4.31).

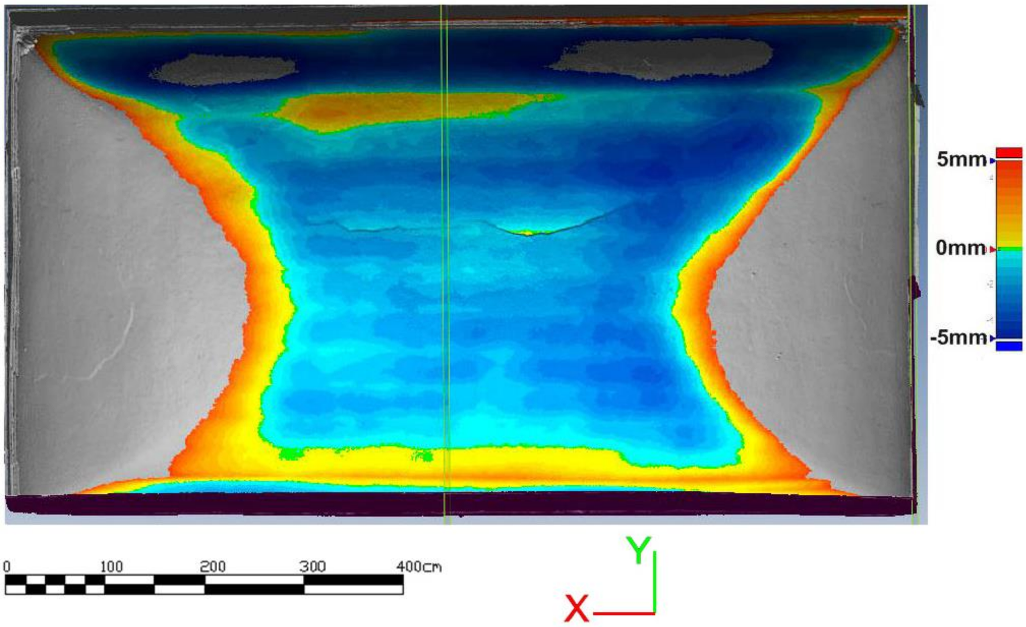


Figure 4.31. Actual 3D model - Cylindrical surface error.

Analysis of the Development Methodology

In order to achieve a planar development of vault geometry and texture using well known and easily available software tools, a methodology using model representation by contours, rather than by ideal shapes such as cylinders, was investigated and applied to this case study.

For this purpose, just the contour lines lying in the XY coordinate plane were used in a CAD environment, with a 20-cm step (fig. 4.32).

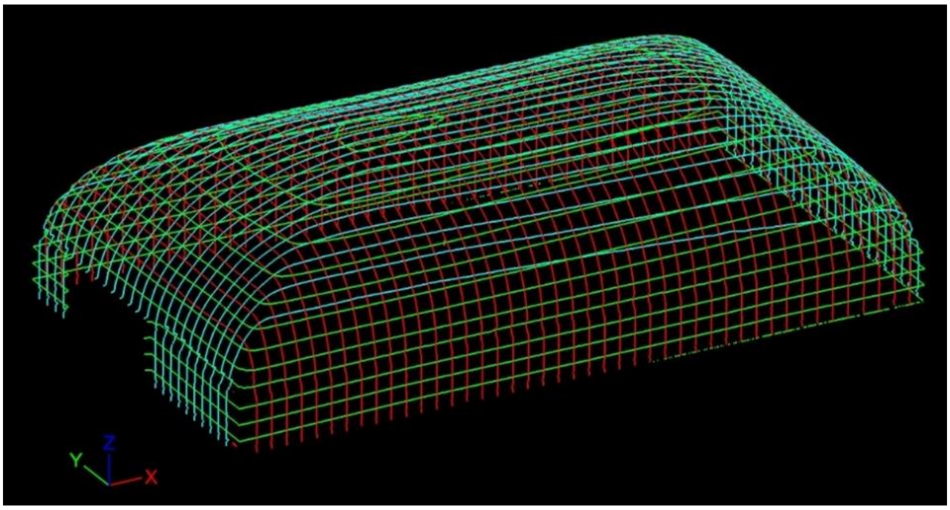


Figure 4.32. 20-cm step contour lines model.

It was assumed that vault sections between adjacent contours were planar. Contours were assumed as connections between adjacent planes. In order to estimate the error introduced by this assumption, an orthogonal section of the interpolating cylinders was checked. In the most unfavorable situation (fig. 4.33), the difference between the section arc Equation (1) and the related chord Equation (2), bounded by two adjacent contours, was computed.

$$\widehat{AB} = \beta \cdot R \tag{1}$$

$$\overline{AB} = 2 \cdot R \cdot \sin(\beta/2) \tag{2}$$

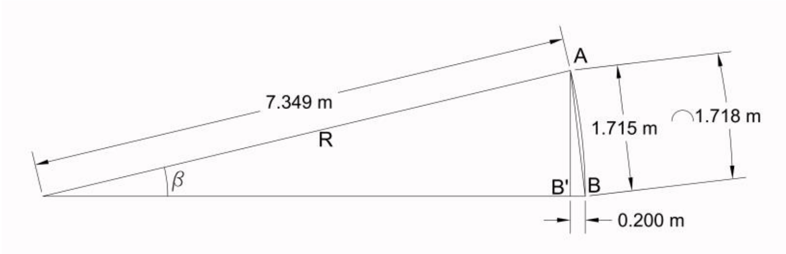


Figure 4.33. Section arc - chord comparison.

On an arc length = 1.718 m, the maximum difference was 3 mm, with a sub-millimetre relative error. This approximation was deemed as acceptable. For the planar development of the XY contour lines model with a 20-cm step (the same used to detect the different portions of the vault), the crown of the vault was outlined in CAD at 1:1 scale (line AB in fig. 4.34).

Subsequent contour lines were separately developed by trilateration for each surface of the vault. Assuming the extremes of the previous contour as fixed points, the extremes of the next contour were plotted. Figure 4.34 shows how planar geometric development of the actual vault lacks the regular course found in the development of an ideal surface constituted just by portions of cylinder with parallel axes.

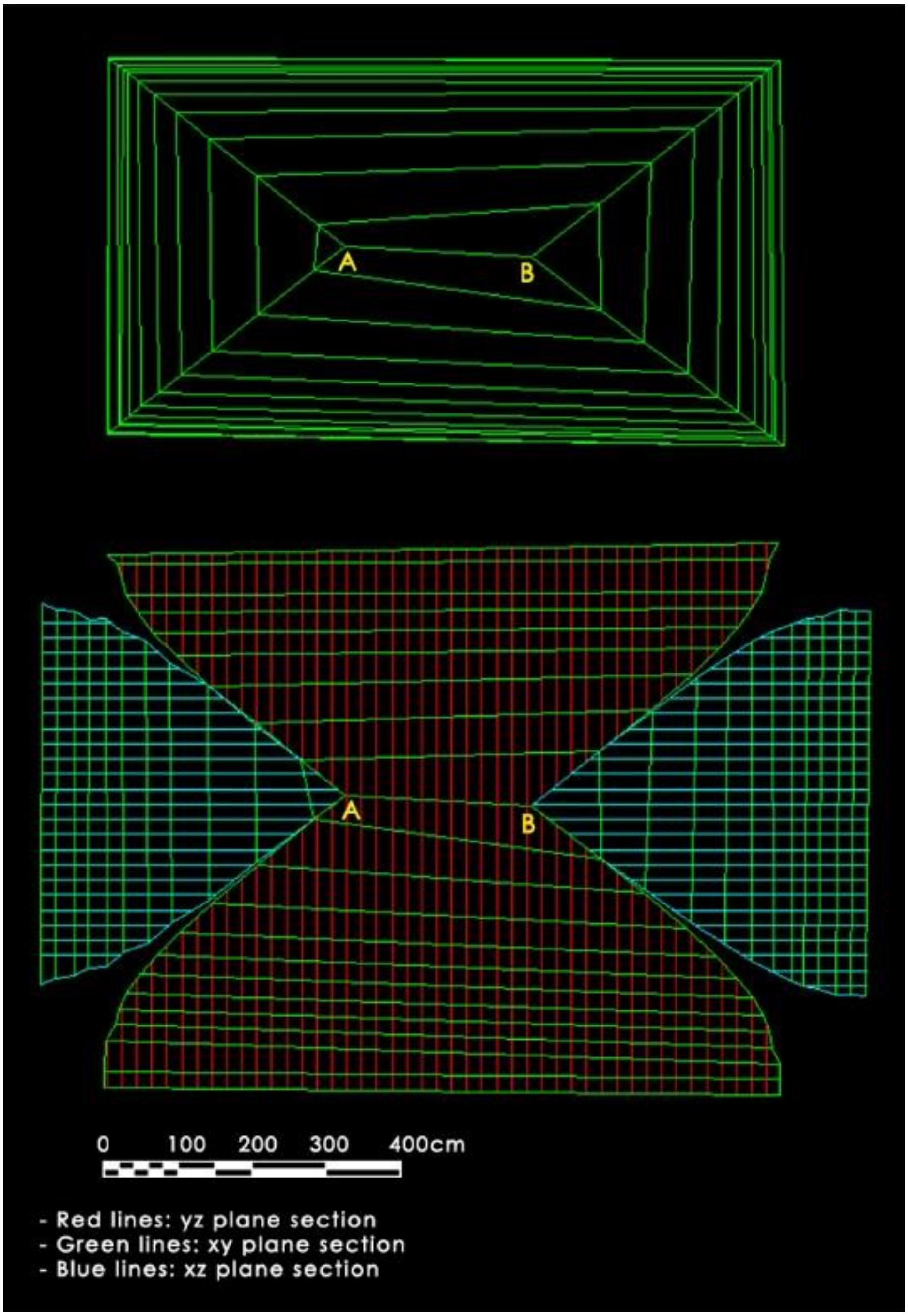


Figure 4.34. Geometric development of contours model.

Sections defined by ZX (blue lines) and ZY (red lines) planes were then superimposed on the development of the XY sections (green lines).

Besides geometric vault development, sections were also required as a reference for correct texture placement on the developed model.

In order to apply textures to the developed geometric model, the following methodology was adopted.

For each surface, eight directions were identified to set orthogonal views of 3D model SfM/LASER. These directions were orthogonal to the axis of the theoretical cylinders and, starting from the horizontal view, tilted by 15° relative to the previous view.

For each viewing direction, images of the model of vault portion bounded by a 15° cylindrical arc were collected. These were an orthogonal projection of the vault texture on an orthogonal plane relative to the viewing direction (Meyer, et al., 2006). Fresco elements projected in this way were obviously deformed.

Accepting the simplification that the vault was represented by the surfaces of the interpolating cylinders, it was possible to quantify this deformation. As for the orthogonal projection on a plane tangent to the cylinder, there was no deformation along parallel directions relative to the tangency line, while deformation was highest along orthogonal directions. Linear deformation module (m_l) at the extremes of the orthogonally projected area was defined by Equation (3).

$$m_l = \frac{\overline{AB'}}{\widehat{AB}} = \frac{2 \cdot R \cdot sin(\beta/2)}{R \cdot \beta} \tag{3}$$

In the projection used, deformation was highest in the furthest point relative to the tangency line (for breadth = 15°, distance is about 1 m), where m_l = 0.9970 and deformation = 3 mm (fig. 4.35).

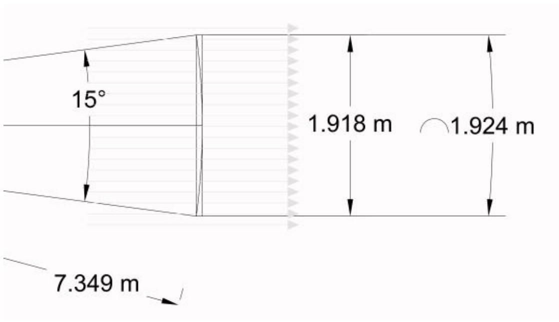


Figure 4.35. Projection deformation.

In accordance with the operators involved with the restoration of the fresco, this deformation was deemed acceptable.

Each orthogonal view of model SfM/LASER was performed in two configurations and saved in two separate image files. Configuration 1 provided for superimposing the section lines to the model (fig. 4.36a). Configuration 2 provided a view of the model with just the high quality texture applied (fig. 4.36b).

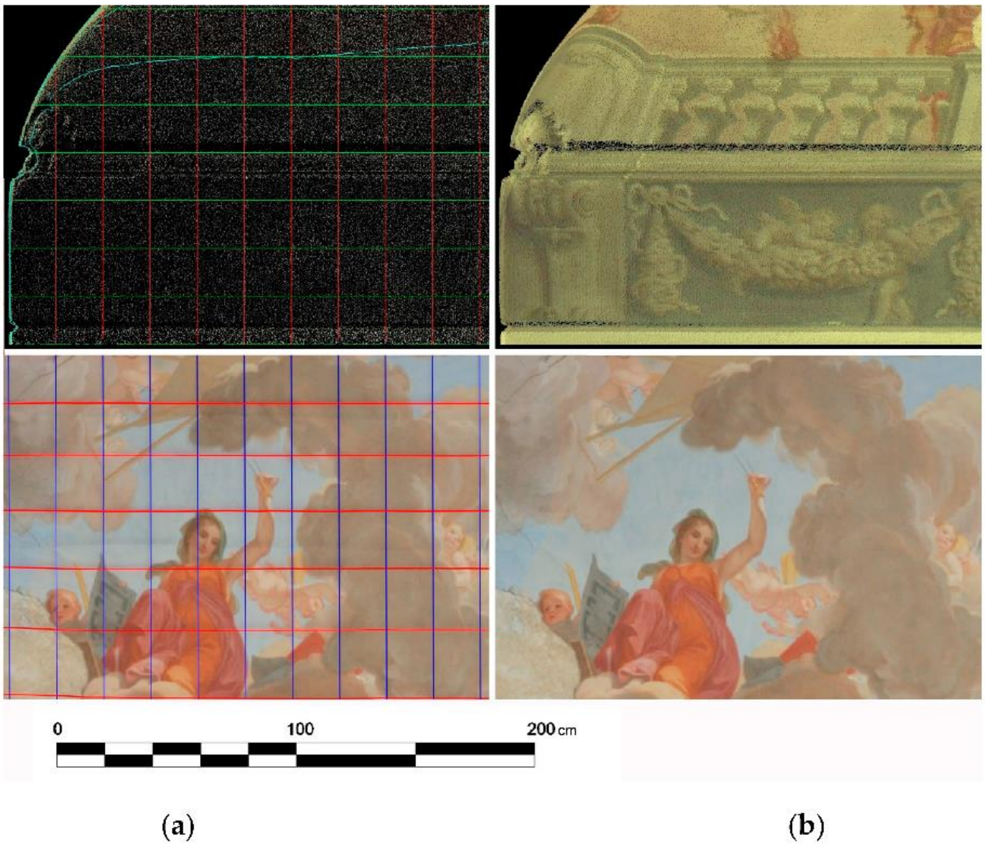


Figure 4.36. (**a**) Orthogonal view with section lines; (**b**) Orthogonal view with high quality texture.

The following processing steps were therefore followed for each image pair:

- Image pairs and the geometric vault development frame (fig. 4.34) were imported in the same photo editing software environment.
- A single block was created with both images, so that any transformation applied to any one image was similarly applied to the other.
- The layer containing the image with just the texture was turned off, leaving visible just the image with the section lines.
- The image was scaled and moved on the geometric frame, assuming the section lines obtained with XZ and YZ planes (vertical lines in fig. 4.36) as reference.

As proof of the small deformation of the images, it was noticed that, after scaling the image in the direction of the axis of the interpolating cylinders for a single projection direction, it aligned with images derived from other projection directions at less than the computed deformation (fig. 4.37).

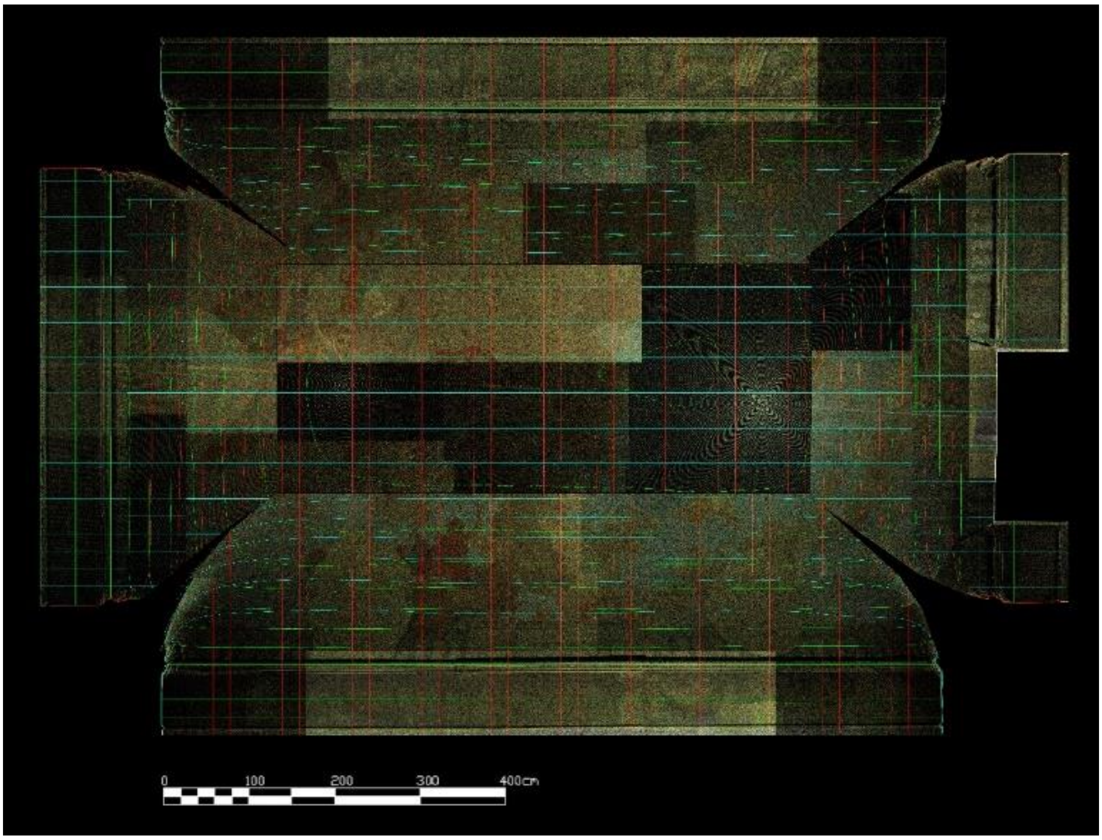


Figure 4.37. Superimposition of orthogonal view on sections model development.

Vault Development Accuracy Assessment

As already mentioned in the comparison section, besides the 3D comparison between Model SfM/LASER and Cloud LASER, planar development was also validated at 1:1 scale (fig. 4.38). The resulting accuracy was similar.

Figure 4.38**.** Development accuracy assessment at 1:1 scale.

4.4.2.3. Conclusions

The methodology discussed proposed a simplified solution for the problem of a metrically correct planar representation of a frescoed "*a schifo*" vault. The processing steps (table 4.21) shown could be carried out even by relatively inexperienced users and did not require specific software.

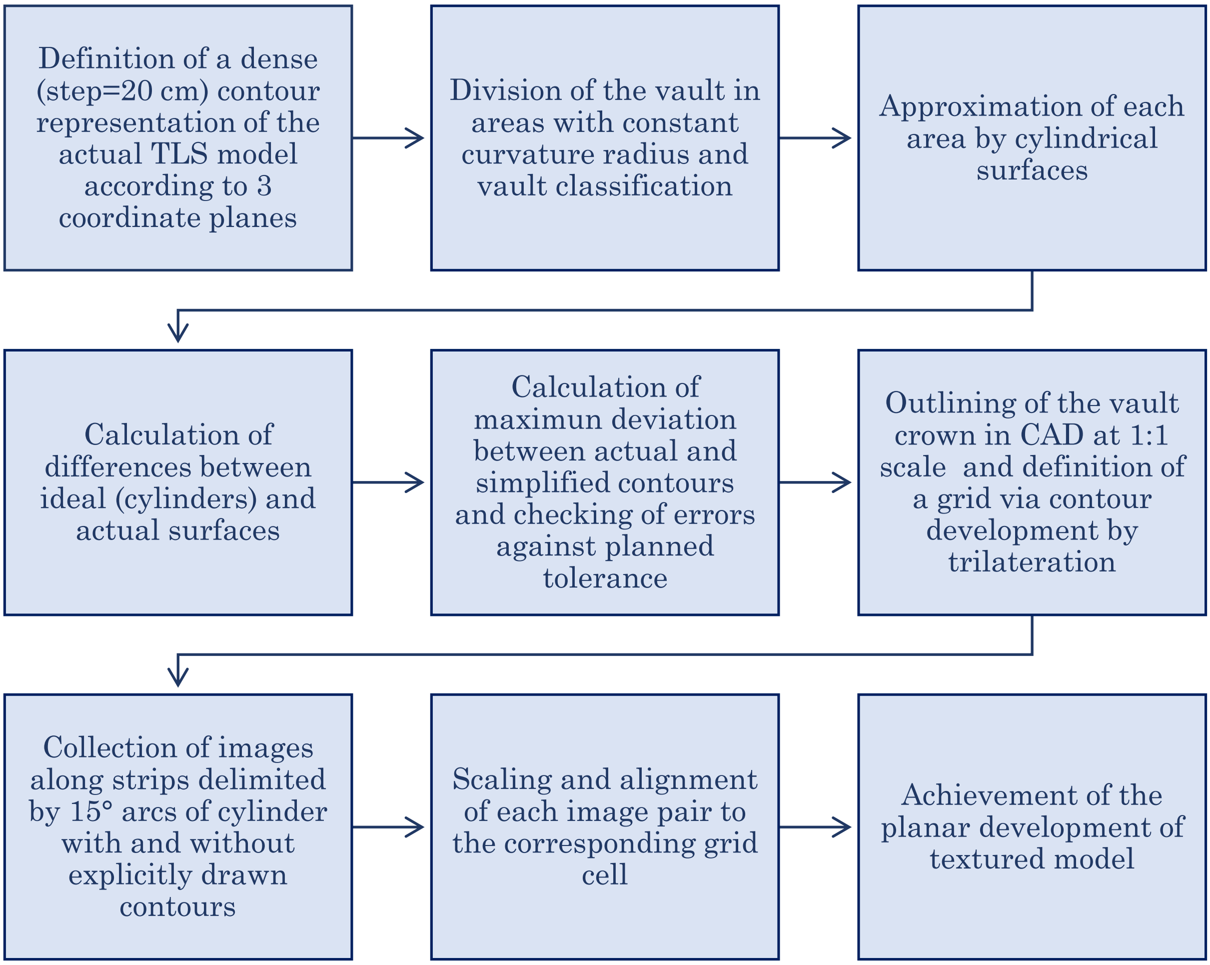


Table 4.21. Diagram of planar development methodology

A peculiar feature of this methodology is the creation of collages of several orthogonal views of the textured 3-D model, thanks to geometrical references provided by the section lines of the model. These lines are visible in the three-dimensional model, its geometric development and on the images used for the collage.

The methodology proposed for modeling, texturing and planar development was verified by both calculating the theoretical error introduced by the single processing step and by comparing the final products with a reference survey and then directly with the surveyed object.

The theoretical development accuracy was 3 mm. The comparison between the TLS model textured with SFM/MVS oriented images and the original TLS point cloud yielded a 3-mm accuracy. Finally, the direct verification of the development of the model confirmed an accuracy of 3 mm, which allowed obtaining drafts fully usable by restorers for 3D fresco reconstruction on a vaulted surface.

In particular, these were most useful for faithful reconstruction of the geometry in damaged fresco portions, for which a photographic documentation suitable for 3-D modelling is available.

The same methodology can also be applied to domes and vaults of different types.

The case study provides a foundation for possible developments, such as automation of the different processing steps, particularly as regards monitoring of deformations and errors introduced in the final representation.

Further interest also lies in investigating differences between developments obtained by extracting contours by actual surfaces or by approximating them to ideal surfaces.

4.4.3. Integrated mixed survey of endangered areas

Emergency surveys forgo the typical standard methodology normally followed for each technique. SfM/MVS techniques require a clearly defined base / depth relation, a camera axis substantially perpendicular to the object, a more or less uniform lighting, a defined base between shots, an overlap between photos > 50-70%, and so on. Terrestrial laser scanning requires clean working sites, connection between scans by pattern recognition or target in common, a certain defined distance, and so on. All these conditions are compromised when emergencies break out and what could possibly be managed with a single technique in a normal situation requires instead developing new combinations of existing techniques.

4.4.3.1. San Miniato church

The result of the integration was a complete three-dimensional model (Martínez-Espejo Zaragoza, et al., 2015B). From this model (fig. 4.39), several orthophotographs of the various exterior façades and sections of the interior of the church were obtained. The representations obtained in this model yielded a detail with good accuracy for typical architecture scales ranging from 1:20 to 1:50.

As already mentioned in the section 4.3.4.2., the geometrical precision obtained from TLS was in the order of 1cm, while the graphic resolution of the applied texture was higher and coincided with the linear dimension of the pixel, in the order of 1mm. This allowed reading of very small elements (e.g. rifts, cracks, deformations, etc.). This statement was confirmed by the orthophotographs generated from ground-based surveys.

In parts not coverable by TLS surveys (e.g. roof), SfM/MVS methodology proved very helpful. The model obtained by this technique showed heterogeneous accuracy, though overall comparable to that obtained by laser scanning. The photographs used in SfM-MVS generated high-resolution textures.

From plans obtained, it was possible to generate a complete restoration project. The resulting sections could be used to analyse small displacements, either vertical (due to subsidence for changing of water table, nearby excavations...) or horizontal (due for example to push from the cover), wall thickness, presence of voids (windows, doors, etc.), current status of the wood trusses of the cover, and, thanks to the addition of the UAV-based survey, the status of the roof tiles and the roof in general (e.g. areas with missing tiles, not noticeable from the ground).

The roof model, and the plan hence generated, allowed to detect several points where the replacement / integration of some tiles was needed. With this intervention, it was possible to remove some water leaks caused by a bad preservation state of the roof.

This type of survey would also allow for regular monitoring that would cut down the high costs connected with water leaking in the interior of a church, with all that entails.

Figure 4.39. Render of the church from integrated surveys

Although the case study did not refer to an emergency, it allowed to carry out some tests that would be useful for the two next case studies, where the situation does not allow to carry out the suitable tests.

Analysis of pathologies for further intervention

From the three-dimensional model of the church, orthophotographs were generated, in order to conveniently investigate the pathologies detected in the building. Results of these investigations were subsequently analysed and the necessary solutions to intervene in the process of restoration were produced.

Two examples are presented in the orthophotographs of the roof and facade. The resolution of textures obtained from models developed with SfM/MVS allowed to detect the pathologies present in the church. In the detail below (fig. 4.40) two pathologies can be identified: one consists in missing or broken tiles (detectable by the naked eye), and the other is biodeterioration (pathology more widely present in the church), consisting of yellow patches in most of the tiles, masking their original red colour.

Broken or missing tiles, besides aesthetic issues that can be overlooked due to their location, can eventually lead to water flowing along the façades, and water leaks inside the church. Flowing of water along the façade leads to biodeterioration, due to the porosity of stones, in which it is retained, leading to germination of spores and seeds and ultimately to presence of microorganisms, lichens, etc. Leaks, on the other hand, can cause well-known damage to the interior due to introduction of water.

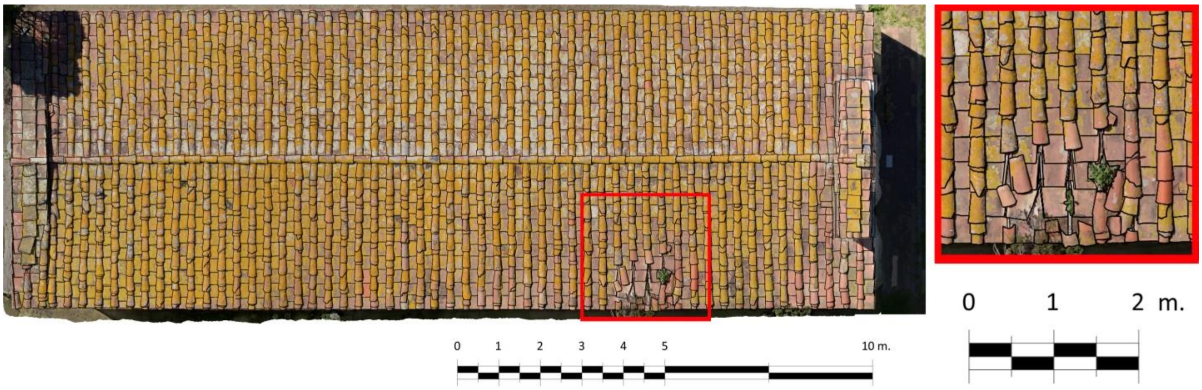
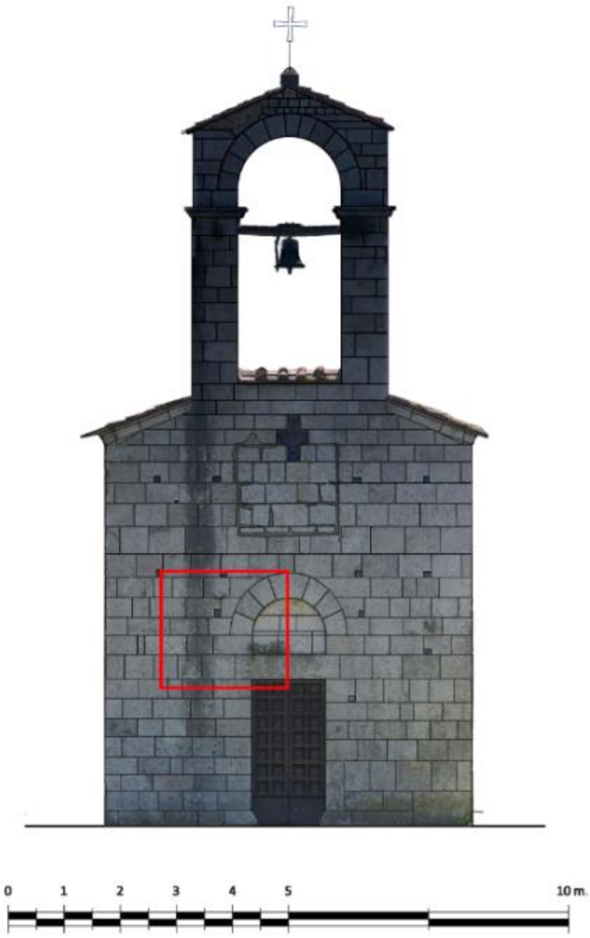


Figure 4.40. Ortophotograph of roof (left) and detail (right).

Moreover, a detail of the façade (fig. 4.41) reveals pathologies such as vegetation, due to the presence of water along with spores and seeds, and black crusts. These are an evolution of biodeterioration, i.e. while in the latter attacking microorganisms are active, in black crusts involved microorganisms are no longer active and concur to the creation of a layer of dead material that hardens and thickens over time, due to the adhesion of dirt and other particles.

Another noticeable pathology is alveolization or disintegration. Higher humidity levels in north facing façades, along with scarce – if any – exposure to direct sunlight, cause partial dissolution of stones due to flowing water.



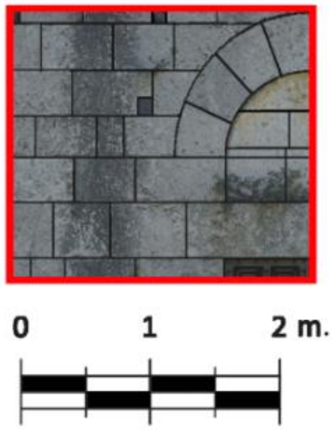


Figure 4.41. Ortophotograph of main façade (left) and detail (right).

4.4.3.2. San Francesco church

The methodology used (Martínez-Espejo Zaragoza, et al., 2015A) allowed to obtain a complete textured model of the survey object, with few gaps. This was used to generate several outputs, such as verticality maps and horizontal and vertical sections.

Verticality maps

The integration of TLS and SfM/MVS surveys enabled creation of complete verticality maps. The analysis of these allowed the identification of areas out of alignment, cave-ins and fractures on the walls due to earthquakes. With respect to middle planes of the respective walls, in the figure 4.42 in the left, an outward displacement of the top part of the wall is evident, while on the right there is evidence of swelling of the wall in the central area.

Horizontal and vertical sections

Starting from a model derived from both procedures, vertical and horizontal sections of the church were created, useful for drafting the entire project of restoration. In sections resulting from the sum of partial processing, it was possible to analyse fractures, gaps, ceiling beams, changes of position, etc. For example, fig. 4.43 (right) clearly shows some fractures on the wall. This information is very useful for the planning of the restoration project. From the completed model, engineers can have a complete vision, which would not be possible even visiting the site.

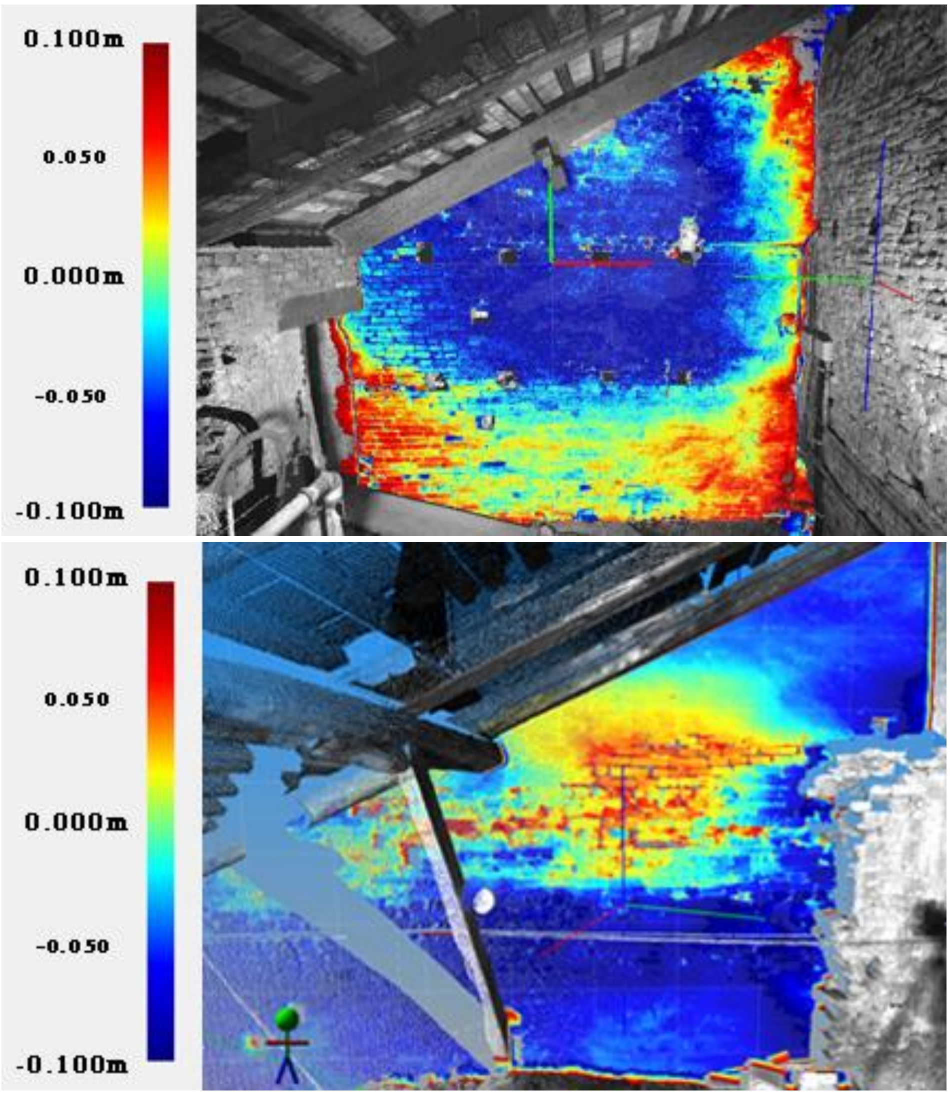


Figure 4.42. Deviation maps of the wall respect to a vertical middle plane

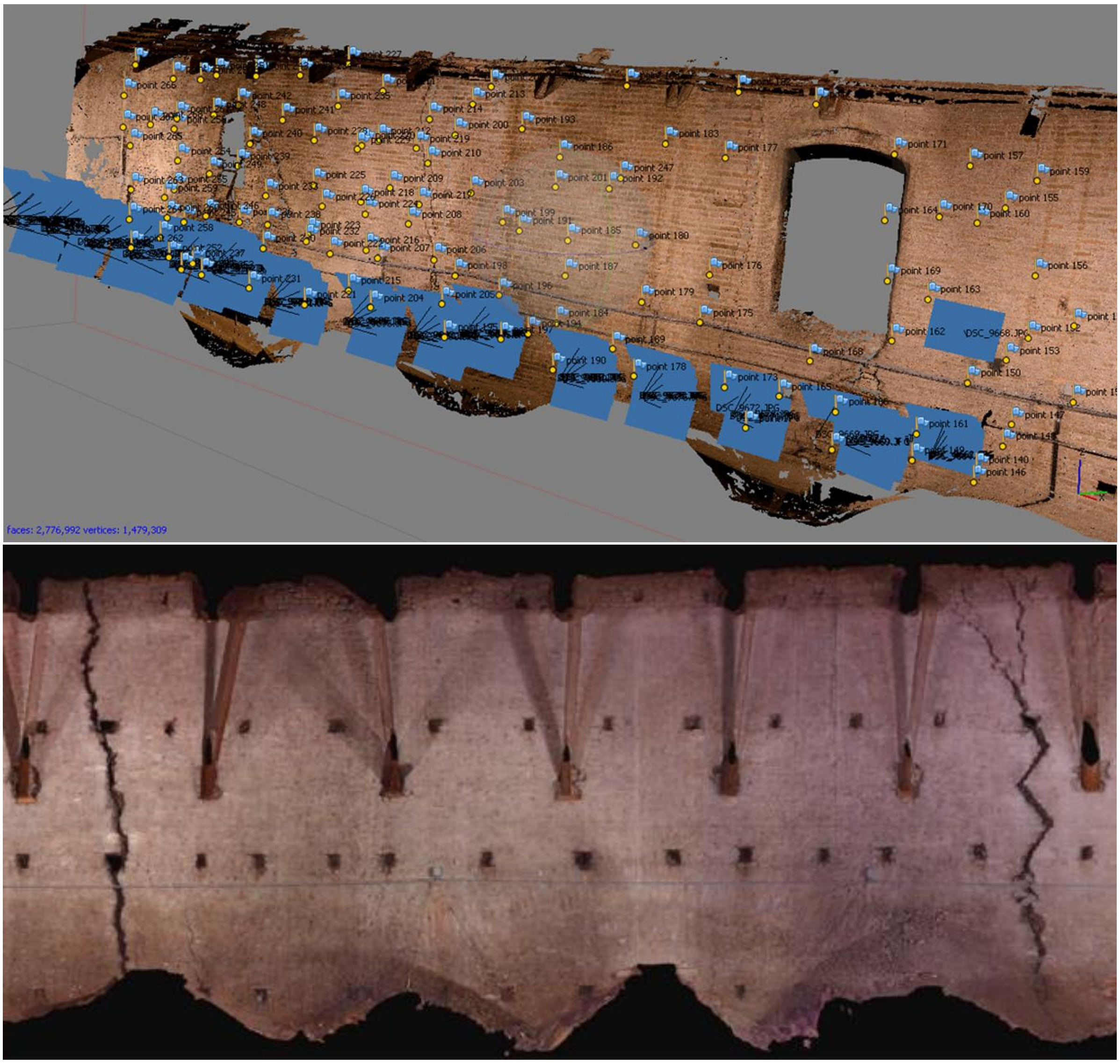


Figure 4.43. Above, imaging geometries and, below, an example of damaged wall portion.

4.4.3.3. Harzburger Hof hotel

From the processed data, a complete model of the external hotel part was generated from the integration of the various parts obtained from the different techniques (fig. 4.44) (Martínez-Espejo Zaragoza, et al., 2017).

The results seen in the section 4.2.3.3. confirmed that, in case of necessity due to emergencies, integrating TLS with UAV-based photogrammetry can be quite effective.

Figure 4.44. Two screenshots of the integrated model.

Thus, thanks to model integration, it was possible to study the current situation of this building in order to draft a safety intervention plan and a subsequent restoration project, according to requirements.

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Menna, F., Rizzi, A., Nocerino, E., Remondino, F., Gruen, A., 2012. High resolution 3D modeling of the behaim globe. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2012**, *39*, pp. 115–120.

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5. CONCLUSIONS

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This thesis allows drawing some conclusions for the fully developed work, as well as some others specifically dealing with four particular aspects of the research.

5.1. GENERAL

Within the broader field of study "low cost Terrestrial and UAV-based photogrammetry for Geomatics applications" this thesis focuses on four aspects in order to provide an operating methodology for surveys related to architecture and cultural heritage:

1-Influence of GCPs/tie points in SfM and MVS techniques

2-Best methods for survey assessment

3-TLS/SfM-MVS integration

4-Original applications in architecture survey

The first three aspects are closely related and mutually influence each other.

As each aspect is investigated, it is easy to verify that each depend on the others, thus, it is noted that the integration of laser scanning and SfM-MVS depends directly on GCPs/tie points number and layout, as well as correct verification of the surveys for accuracy and precision.

Moreover, it is also possible to deduce that the use of GCPs is crucial for a correct assessment of the survey. This is due to the fact that GCPs are used to set up the different models on the same reference system. Inadequate choice of GCPs might yield biased results, which in turn would impede correct placement in the common reference system and ultimately prevent computation of true deviation values between models.

For these reasons, although each of these aspects has been analysed separately, mutual relationships have been checked throughout the thesis.

On the other hand, the last aspect ("Original applications in architecture surveys") reflects the previous three, since the results depend directly on the chosen options and the results obtained from these. This allows applying this methodology to complex cases, such as the use of surveys with multiple integration in risk areas surveys, or atypical, such as planar development of frescoed vaults.

Accurate analysis of these four aspects allows to define guidelines for low-cost terrestrial and UAV-based photogrammetry, which in turn enable generation of a workflow intended for use by any figure involved in surveying in architectural and cultural heritage contexts.

5.2. ASPECTS OF THE RESEARCH

Each of the aspects studied suggests a series of conclusions, which are outlined below:

5.2.1. Influence of GCPs in SfM and MVS techniques

The conclusions that can be drawn from the San Miniato and Harzburger Hof case studies include many points, some of which are reflected in Caroti, et al., 2015A and Martínez-Espejo Zaragoza, et al., 2017.

The tests reported corroborate results already available in literature, i.e. that higher numbers of GCPs, evenly distributed both along and orthogonally to the photographic axis, increase model accuracy; besides, this has proven to be true particularly when surveying objects effectively spread in three dimensions, while no substantial improvements in accuracy have been detected in planar elements, such as façades (Caroti, et al., 2015A).

While overall model accuracy is to some extent directly related to the number of GCPs and of images, test carried out during the development of the thesis allow to point out some clarifications. As regards GCPs, a well-planned layout requires comparatively few points in order to achieve accurate models. On the other hand, detail levels improve upon processing up to 6 images of the same object, with the most sensible improvement upon processing the third image and no useful effect after the seventh. Besides, as increasing GCP and/or image numbers affects working time and therefore costs, and based on the tests performed, it is possible to state that “more” does not necessarily translate to “better”, and that it is therefore most important to plan photogrammetric surveys so that any object appears on approximately 6 photos, each of which also shows at least 3 GCPs.

On the other hand, in the San Miniato case study, in order to simulate a hypothetical rapid survey, the GCPs were identified by on-site details, rather than marked with dedicated targets, and their layout was affected by logistical constraints.

Although rapid surveys save costly operations, they are, on the other hand, more prone to errors related to a difficult and less accurate collimation on the images. This is also corroborated in the case of Harzburger Hof, where some manual tie points do not correspond to *ad hoc* targets. Therefore, it can be stated that whenever possible, the use of *ad hoc* targets is always advisable for the achievement of the planned accuracy degree, otherwise the loss of accuracy due to the use of natural targets must be taken into account.

Moreover, from the tests carried out in Harzburger Hof as reported in section 4.1.4.2., concerning manual input of tie points to a model calculated with some GCPs placed heterogeneously due to emergency and inaccessibility of the building, it is possible to state that higher number and homogeneous layout of the tie points entail higher-quality modelling.

It should be remarked, however, that user selection of tie points, is not always necessary, since different tests on case studies have shown that software-selected tie points were sufficient (at least) in some cases.

After automatic feature extraction and matching, which enable tie points selection, it is necessary to ensure that the points are correct, in sufficient number and homogeneously laid out. Otherwise, user selection of tie points is necessary before dense point clouds calculation. In the next step, i.e. dense point cloud processing, a comparison is already possible between the methods commented in section 4.2 (best method for survey assessment).

It can be concluded, therefore, that the use of black box software can provide great advantages, as long as each of the processing steps can be carefully checked.

5.2.2. Best methods for survey assessment

The Palazzo Roncioni case study allowed investigation on three different types of comparison. The process has shown that no single method can be denoted as the most globally appropriate, since some methods will not be usable at all in certain situations (comparison with actual objects is impossible in many cases), and will be more or less suitable in others, depending on the purpose or the type of survey.

The comparison of the complete vault model allowed checking that the CP-based method might not reflect its accuracy as a whole, due to lower accuracy only in regions showing damages such as gaps or cracks. Therefore, accuracy will be higher if the chosen points are all along the vault in frescoed areas, with no gaps or cracks, while if the chosen points are in damaged regions accuracy will decrease. Moreover, local meshing as created in some comparison typology tends to soften sharp features, which may be important in some cases, such as cracks.

In San Miniato it was impossible, with limited resources, to obtain a TLS virtual model of the roof, as well as to compare the virtual image-based model with the actual object. In this case, therefore, the possibilities were confined to the CP method. On the other hand, the results of both comparisons (virtual models comparison and virtual model with CP) for the façade, where both image-based and laser scanning models were available, were similar.

In the Harzburger Hof case, the building was inaccessible, so that direct comparison with the actual object was not possible. In addition, the limited field time did not allow collection of data that would have allowed to obtain a more complete TLS model. This data comparison was performed directly between the TLS and photogrammetry point clouds, noting the need to select areas with a roughly homogeneous point density in order to obtain results reflecting reality, avoiding distortions due to the lack of points in either point cloud.

In this case, the different possible data comparison types have been tested, without introducing new methods or improving existing ones, but rather suggesting a methodology covering each one of the 4 points described in the thesis in order to obtain a well-structured complete process. It is important to analyze each aspect individually, even if it is ultimately part of a whole.

5.2.3. LS/SfM-MVS integration

The Palazzo Roncioni case (Caroti, et al., 2015B) pointed out that the suggested methodology allows obtaining a three-dimensional model retaining the geometric precision of TLS surveys along with the texture quality attainable with a photographic survey campaign.
On the other hand, the ability of integrating photogrammetry and TLS allows obtaining more inclusive models in cases where time (Harzburger Hof), safety (San Francesco) or cost constraints (San Miniato) prevent full accessibility to the survey object. The introduction of UAV-based techniques greatly reduces security risks by allowing access to otherwise non-accessible areas.

Results presented in Martínez-Espejo Zaragoza, et al., 2016 show how, in case of necessity due to emergencies, integrating TLS with UAV-based photogrammetry can be quite useful.

This paper shows that UAV-based photogrammetry is comparable in terms of precision to TLS in parts lying almost orthogonally to the shooting axis, and provide a useful solution to integrate the survey of roofs, gardens and inner courts, for which stability issues prevent accessibility.

On vertical parts, instead, UAV-based photogrammetry with nadiral shooting axis provides lower quality. However, the ability to use UAV-based surveys also to process regions acquired with limited view angle, such as vertical walls, is surely interesting.

In fact, as the rendering scale for these portions will not be the same as for sub-horizontal parts, the survey allowed the restitution also of all inaccessible and vertical internal walls of the building, with structural stability issues.

Moreover, in the case of San Francesco, stability issues, narrow passages and debris accumulation in many areas all concurred to prevent data collection with either technique. However, integration of both techniques allows generating a complete model of the general condition of the study area.

All these solutions allow to conclude that the proposed methodology allow to obtain solutions with greater productive efficiency considering all limitations of both techniques, TLS and SfM-MVS.

5.2.4. Original applications in architecture survey

The different studies carried out during this thesis provide a solution to the different problems faced in the case studies. As an example, the vault case presents a real problem that was solved reducing many hours of work.

The methodology discussed suggests a simplified solution for the problem of a metrically correct planar representation of a frescoed vault. The processing steps shown can be carried out even by relatively inexperienced users and do not require specific software (Bevilacqua, et al., 2016). Moreover, the same methodology can also be applied to domes and vaults of different types.

On the other hand, thanks to survey integration it was possible to obtain the current situation of the church and hotel, each presenting major security problems, and develop models to create an action plan for further intervention. The ability to map pathological conditions allowed for their quantification and analysis directly in the office without having to spend time in the field, in many cases in unsafe conditions.

Anyway, it is possible to conclude that a new workflow has been defined, where integration of the aforementioned research aspects has allowed to achieve an optimized survey, providing accuracy checks of the acquired data and integration of data from different sources, as well as accuracy controls of both each single-technique model and models obtained through technique integration.

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6. ACKNOWLEDGEMENTS

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First of all, I wish to express my gratitude to Prof. Ing. Gabriella Caroti, for becoming my role model, my reference as to where I would like to arrive. Almost 5 years ago, I arrived in Pisa, disoriented and a little lost, looking, as she once told me, like an abandoned puppy that did not know where to go. She welcomed me not only as a tutor but almost as a mother, struggling to support me whenever necessary and facing the different storms that have accompanied me along these years; she has always made me feel truly valued, teaching me and helping, without ever losing her trust in me. I am however grateful not only at a personal level but also at a professional level. I have been able to perceive with ever-sharper detail the difficulties of her position, which she always faces with the utmost integrity thanks to her determination in the key moments and strength when she has to defend her ideas. For all of this, I can do nothing but admire her, and hope someday to be able to resemble her.

I would also like to give my sincere thanks to Andrea, who, besides being a source of seemingly inexhaustible knowledge, is the personification of understanding and patience. I want to thank him for all the conversations, which have helped me to go ahead when my positive thinking was hidden and refused to surface, for always having the right words of advice and offering a different perspective of the most complicated situations. I want to thank him sincerely for all the help, the closeness, the availability and sympathy that have allowed me to understand that he always has the door open to give his advice when the way is not so clear.

To Professor Wolfgang Niemeier, for accepting me as his PhD student and making my internship in Germany surprisingly warm, for his sympathy, for his advice, for supporting me and helping me face several unnamed fears.

To Professor Audrey Martin, for opening the doors of DIT, always treating me with the most exquisite sympathy and always being available to help me and to make my stay in Dublin as pleasant as possible, at both professional and personal levels.

To Marco Bevilacqua, Bjorn, Eugene McGovern, who, being teachers not directly linked to my doctorate, taught me a lot, always being available and helping me whenever I needed them.

To Federico Capriuoli, for collaborating with me in several occasions, for always being there to help me, to value me and make me feel valued. Above all, thank you for showing me that there are still real good-hearted people, willing to help without expecting anything in return, just because they are like this. Thank you for that nobility that characterizes you and makes you so special.

To Andrea Bedini, for being my "*babbo italiano*", for always taking care of me, for worrying like a father, for always having the door open and for having this admirable personality that puts before him to all people. And if it should not be enough, for the infinite patience of revising the English form of my whole thesis, reading, reviewing and proofreading it with me, without ever showing what should be legitimate, which is a deadly boredom. Thank you.

To my colleague Jessica Micheloni, for her constant support since I arrived, for sharing each of my achievements to make them twice as big, and many of my sorrows to cut them in half, and for never failing to give an advice on both professional and sentimental plans.

To all the people who supported me along each survey, Mr. Luca Mariotti of CAM - Pisa, the members of the IFF - Braunschweig, Mr. Marco Bisdomini of Hera - Ferrara, and all those that I have not nominated but have also been a support without which I wouldn't have been able to conclude this work.

To Professor Pedro Collado, who, since we first met and I chose him as director of my final project, has always kept on supporting me and helping me, always recommending me the best ways to achieve my dream.

Also to the office colleagues, that I met in my internship outside Italy, and especially to Armagan and Antonello, for thanks to them the distance from home was felt to a lesser extent, and they have made me feel very fortunate.

To my family, who has endured all my moments of incomprehension, difficulty, willingness to give up ... and, in conclusion, all those moments that a person faces in the course of a very hard and intense work. Thank you especially to my mother, for the support she has given me, even along my most difficult times, when I confided her everything, although we both knew that in the distance she could do nothing but listen to me and pray a lot, as she has always told me that she would do. I apologize now for having made her suffer by giving her that feeling of helplessness borne out of distance. I want that she knows that she has helped me so much, that she is the most faithful person I have ever known in my life and that I love her with all my soul. Thank you for that blind trust, which at times I wasn't able to feel myself, that I would succeed. Thank you for your dedication, for always putting me in front of all your needs, for being my constant support always, an "always" with capital letters that makes me feel really lucky. Thank you for being that mother that everyone dreams, and that for me is a reality.

Thank you, in general, to all the people who in one way or another have helped me and supported me to be able to carry out this thesis, and without which I could not have made it.

Finally, I want to thank my friends, both Spanish and Italian, for helping me to continue my work day after day without giving up on those days when everything seems to be wrong. In particular, I want to thank more specifically two people. The first is my friend Claudia, who has been there almost from the first day I arrived in Pisa, always giving a hand, talking about our things and everything in general, sharing pains and joys. We have separated and met several times but always being there, available to each other, being my little Italian sister, being my friend without confines, being that example of frankness, sweetness and kindness that has allowed me to dream in this world where more and more coldness, lie and selfishness predominate.

The other person that I want to thank so much is Maurizio Ginghiali, it may seem misleading the position in the acknowledgments, but remember that many times in the articles the last author is the most important. Either way, the words are not enough to thank you for everything you do for me, as you are able to cross half Europe to come and save me, as you can handle any problem to get me happy, as you move heaven and earth to snatch a smile from me, how you spoil me and how you have supported me every moment, so that I was able to write this in time and achieve a project that seemed impossible. Sometimes there are no words, sometimes words are not needed... you know everything you have done and what you do every day, thank you.

Isabel Mtnez-Espejo Zaragoza